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FRAMES OF REFERENCE FOR ELECTRONIC MAP DISPLAYS: THEIR EFFECT ON  
LOCAL GUIDANCE AND GLOBAL SITUATION AWARENESS DURING LOW  
ALTITUDE ROTORCRAFT OPERATIONS

BY

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EFFECT ON LOCAL GUIDANCE AND GLOBAL SITUATION AWARENESS  
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This study sought to examine frame of reference for electronic map displays and determine its effect on pilot local guidance ability and global situation awareness (GSA) during low altitude rotorcraft flights. It was hypothesized that the egocentric viewpoint would support superior local guidance ability, the exocentric viewpoint would facilitate better GSA, and the Situation Awareness Rating Technique (SART) would not be a good measure of GSA. Eighteen pilots flew simulated missions on six possible paths, with three paths flown at 200 feet and three paths flown at 1000 feet. All participants flew both a low altitude and a high altitude scenario with each of three display viewpoints (egocentric, exocentric, 2D), for a total of six missions. Results revealed that the forward field of view present in the simulation appears to mute the effect of display type on local guidance ability such that all three of the viewpoints evaluated provided equivalent navigation performance. The results for the level of GSA achieved revealed that the egocentric viewpoint suffered with regards to facilitating GSA, but no differences were revealed between the exocentric and 2D viewpoints. Furthermore, the GSA results suggested that the SART may not be a good measure of global situation awareness. Results are discussed in terms of map display design for rotorcraft cockpits.

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## INTRODUCTION

Leonardo da Vinci's design of the helical air screw, in 1480, is commonly regarded as the first concrete conceptualization of a helicopter. However, actual vertical flight did not occur until Nov 13, 1907, when Frenchman Paul Cornu made the first free flight entirely without assistance from the ground, during which he achieved a height of one foot for twenty seconds. From this point in time, the helicopter has evolved into one of the aviation community's most versatile platforms, in that it can perform a diverse range of missions in a variety of different environments, often while flying at very low altitudes. Although this versatility has contributed to the helicopter's utility, it has also resulted in rotorcrafts being exposed to a number of unique hazards and situations during flight that impose significant visual, perceptual, temporal, and motor demands on the human pilot (Hart, 1988; Padfield, 1992). Recent research conducted in the fixed wing aircraft domain has shown that advances in glass flight deck display technology may help alleviate pilot visual and perceptual demands, by allowing the presentation of navigational information in a three-dimensional (3D) electronic map display format (Olmos, Liang, & Wickens, 1997; Olmos, Wickens, & Chudy, 1998; Wickens & Prevett, 1995; Wickens, Liang, Prevett, & Olmos, 1996). However, very few empirical studies have been conducted that evaluate whether these advantages are also present when 3D electronic map displays are used in the context of a highly dynamic, low altitude rotorcraft environment.

The helicopter is unique in that its versatility makes it capable of performing missions that often dictate that the aircraft be flown at low altitudes, which requires special perception and control requirements. Flach and Warren (1995) described some of these requirements by stating that low level flight requires that a pilot have precision and responsiveness of control almost to the level of prescience. They stated that precision is demanded because a small deviation in

altitude of only a few tens of feet may translate into clipping a tree or other hazard. Likewise, responsiveness is demanded because the speed and distance at which the flight occurs results in an extremely fast "closure rate", which leaves a pilot little time to act to achieve mission objectives or to react to avoid a collision. This means that the fast changing spatiotemporal relationship between a rotorcraft pilot and the low altitude environment forms a highly dynamic and unforgiving ecology, where there is an ever-present danger to each moment of action or inaction.

This ever-present danger arises from the fact that low altitude flight places a pilot in continuous proximity to terrain and hazards placed upon the earth (Hart, 1988; Padfield, 1992), which is not an environment conducive to safe flight. This low altitude flight environment was poignantly described in the following statement:

In the case of the rotary wing aircraft, the world is indeed a horrible and frightening place-it's full of obstacles-the earth is one, but on top of the earth are literally thousands of obstacles [the pilot] has to wind his way through. And [the pilot] told us that he wants to have information about these obstacles....In relation to any obstacle on the earth...[the pilot] has to know how far it is to an obstacle; he wants to know the direction it is; and he wants to know the rate of change of these two things-distance and direction. (Courtney, 1956, p.51).

If the rotorcraft flying environment was a frightening place in 1956, then it has become truly terrifying in recent years, as more and more powerlines and telecommunications towers and antennas have been constructed. Pilots must be aware of these man-made hazards and naturally occurring terrain and weather hazards, while at the same time trying to navigate an inherently unstable aircraft to a desired location in order to meet the mission requirements.

Unfortunately, research has shown that rotorcraft pilots sometimes have very little time to do anything beyond the actual navigation of the aircraft. An empirically validated task analysis of nap-of-the-earth and low-level helicopter operations found that helicopter pilots devote approximately 70% of their time to navigational activities when flying in an unfamiliar environment (Shaffer, Hendy, & White, 1988). This means that there is little time and few resources available for the pilots to obtain and maintain sufficient awareness of their surroundings, or what many term achieving situational awareness (SA). Because of the numerous hazards present within the helicopter's low altitude flying environment, a low level of pilot situational awareness can have disastrous consequences. Therefore, the goal of the research presented here is to evaluate how different frames of reference for electronic map displays affect a pilot's local guidance ability and situation awareness during low altitude rotorcraft missions.

Since our evaluation of the effects of different electronic map frames of reference will be based on the pilot's ability to maintain local guidance and achieve situation awareness, it seems appropriate to discuss these two tasks as they apply to the rotorcraft domain. Therefore, we will first define each of these tasks, discuss why they are important, and describe ways in which performance on each task can be measured. We will then proceed with a discussion of electronic map frames of reference and present findings from previous research in this area, highlighting those studies that measured local guidance ability and/or situation awareness. Finally, we will conclude the introduction with a thumbnail sketch of previous research findings, explain our independent variables, and present our hypotheses for this study.

## Assessment methods

In the rotorcraft aviation domain, local guidance and situation awareness are not independent tasks. This is because the two tasks are often performed concurrently during flight (Olmos et al., 1997; Wickens & Prevtett, 1995). However, in order to understand what each is and why they are important, we will discuss them separately in this section.

### *Local guidance*

Local guidance involves maintaining the aircraft on the desired flight path through the three-dimensional airspace (Olmos et al., 1998; Wickens & Prevtett, 1995). This task is considered a form of closed-loop tracking that requires knowledge of one's momentary position and orientation in relationship to the forward field of view (FFOV) seen out of the cockpit (Olmos et al., 1997; Wickens & Prevtett, 1995). The key to local guidance is to have a momentary representation of the error from the ideal flight path, along with an understanding of the required actions necessary to close the control loop and correct that error (Olmos et al., 1997; Wickens & Prevtett, 1995). Because of the demanding nature of low altitude helicopter flight, this can be a nontrivial task.

While it is relatively easy to define the construct of local guidance, being able to determine its relative importance in terms of vertical and lateral error is more difficult. The question is how important is 50 feet of vertical deviation versus 50 feet of lateral deviation? It intuitively makes sense that vertical errors are more important, since there is less vertical space in which to maneuver as compared to lateral space. However, fifty feet of vertical deviation while flying at an altitude of 5000 feet is not nearly as critical as the same deviation while flying at 100 feet. The same is true for lateral deviations. At higher altitudes, lateral deviations from the flight path

may result in the pilot merely becoming lost within the airspace. These same lateral deviations during low level flight can result in the pilot colliding with the ground (if the aircraft is flying in mountainous terrain) or with hazards placed upon the ground. Therefore, the importance for precise local guidance is tied to the altitude of flight at which an aircraft is operating, because vertical and lateral deviations at low altitude flight levels can have drastically greater consequences than the same deviations at higher altitudes. Since many rotorcraft missions require the pilot to fly at low altitudes, where they are always in close proximity to terrain and man-made hazards, the need for precise local guidance during these flights is of paramount importance.

Measuring a pilot's local guidance ability is fairly straightforward and easy in a simulation environment. It involves measuring the difference between the point where the aircraft is at a given time and the point where the aircraft should be (the ideal programmed flight path) at that time. Computer technology allows researchers to measure these deviations throughout the duration of a simulated mission.

### *Situation awareness*

Situation awareness is a ubiquitous term used in the aviation community and is intuitively understood to be a good thing for a pilot to have. A formal definition for this construct was somewhat hard to develop, because SA is a mental process that must be inferred from behavioral evidence, which is not a trivial matter, and therefore the construct was not very well understood. However, Endsley (1988) formulated a widely accepted definition which states that situation awareness is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future".

This definition contains three distinct levels of SA, which she defined as perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean, particularly when integrated together in relation to the aircrew's goals (Level 2), and an understanding of what will happen with the system in the near future (i.e., prediction) (Level 3) (Endsley, 1998).

Within this broad, general concept of situation awareness are certain subsets, or different elements, of awareness that an individual must obtain in order to achieve SA (Endsley, 1998). Recent research by Entin (1998) suggests that in a dynamic and fluid situation, such as an attack helicopter mission, overall detailed SA may actually fragment into a number of relatively independent components. Therefore, where possible, one should refine the definition more specifically to refer to more specific constructs, such as; geographical hazard awareness, automation mode awareness, or task awareness (Wickens, in press). One of the elements which is critical for low altitude rotorcraft missions is spatial, or hazard awareness (Endsley, 1998). Hazard awareness involves being aware of any hazard (e.g., terrain, weather, other traffic, no-fly zones) within some proximity of the aircraft (Olmos et al., 1998; Wickens, Fadden, Merwin, & Ververs, 1998), which is extremely important because of the numerous hazards present in the low altitude rotorcraft environment. While a pilot must be aware of the hazards near the forward flight path, he or she must also have an awareness of the hazards within a 360 degree sphere around the aircraft, or what is termed global situation awareness (GSA) (Olmos et al., 1997; Wickens et al., 1998; Wickens & Prevett, 1995). The need for precise global situation awareness by rotorcraft pilots is necessitated by the helicopter's ability to move backwards while hovering, which means that the pilot must know whether there are obstacles or hazards behind the aircraft.

The true importance of SA becomes apparent by discussing the role that errors in situation awareness play in aircraft incidents and accidents. We will first look at general findings in the

aviation industry, and then present statistics specific to the rotorcraft domain. Jones and Endsley (1996) conducted an evaluation of 143 Aviation Safety Reporting System (ASRS) reports collected between January 1986-May 1992 that included SA errors by either pilots or air traffic control personnel. They found that 76.3% of the situation awareness errors were Level 1 SA, which involved a failure to perceive information or the misperception of information, 20.3% were Level 2 errors, which involved the improper integration or comprehension of information that is perceived, and 3.4% were Level 3, which involved cases in which a projection of future actions of the system was incorrect or missing. The percentage of errors for each level of SA found in the incident reports were very similar to an earlier study by Endsley (1995), who looked at situation awareness errors involved in 24 major air carrier accidents from 1989 to 1992. Of the 32 actual SA errors identified within these major accidents, 72% were Level 1 errors, 22% were Level 2, and 6% were level 3.

Accident statistics specifically looking at the number of helicopter accidents also highlight the importance of SA for rotorcraft pilots. The Flight Safety Foundation performed an analysis of information provided from the Federal Aviation Association's Accident/Incident Database System of turbine helicopters flown in the United States during 1988-1992. During this period, 85 fatal turbine helicopter accidents occurred resulting in 172 fatalities, with 62 of the accidents being attributed to pilot error (Harris, 1995). These 62 accidents were then classified according to a taxonomy developed by the National Transportation Safety Board, which includes six accident categories: weather-related, mechanical failure, obstacle strikes, control loss, midair collision, and miscellaneous. Placing the accidents in these categories revealed that 38 out of the 62 pilot error accidents were either weather related or a result of terrain, obstacle, or midair collisions.

Although this study did not specifically classify these accidents according to SA errors, one can infer that situation awareness played a role in these accidents, since the pilots would not have entered or collided with the hazards if they had been aware of them. Also, if the SA errors present in these accidents were classified according to the level of SA during which they occurred, the percentages found would probably be very similar to Endsley's (1996, 1995) studies. In both of these studies, Level 1 SA errors were the most common errors and were defined as failures to perceive information or the misperception of information. This also seems to be the case for these 38 fatal helicopter crashes, again because the pilots would not have entered or collided with the hazards had they correctly perceived them.

As stated before, there are certain subcomponents, or elements, of awareness that a person must obtain in order to achieve SA (Endsley, 1988). These subcomponents are interactive in nature, such that improving situation awareness for one subcomponent may actually reduce SA on another (Endsley, 1996). Because of this, as well as the overall hypothetical nature of SA, multiple measurement techniques need to be employed to try and fully measure the many different facets of SA present during a particular mission. Relying solely on one measure for situation awareness can yield misleading results, and therefore, each measure must be viewed in the context of other measures of SA (Endsley, 1996). Endsley (1996) provided a comprehensive review of the different approaches and measurement techniques that may be employed to measure SA. Based on her review, we will use the remaining part of this section to briefly describe several of these approaches and techniques.

One possible approach, although it may only give an indirect measure of situation awareness, is to examine the processes used for acquiring SA (Adams, Tenney, & Pew, 1995). This may provide information concerning how an operator allocates his or her attention in using a

particular system design, which could reveal the relative priority of different types of information and the relative utility of information sources. Several different measures may be employed, such as eye tracking, to assess how attention is deployed in the process of acquiring SA, verbal protocols, to gain some insight into how the obtained information is integrated and used in the process, and evaluation of verbal communications, to determine the types of information that is lacking from displays and verbal techniques used for acquiring SA. Although these measures do not provide any insight into how the attended to information is used or combined to form higher level SA, when used in conjunction, they may offer valuable information concerning the processes an individual uses to obtain SA. This information may help in the development of training strategies designed to help individuals take certain steps which may help in achieving overall situation awareness.

Other measures have been developed that assess the product of situation awareness directly, and are usually broken down into three categories: subjective techniques, questionnaires, and performance measures. Subjective techniques usually involve the operator making a subjective estimation of how much SA he or she has when using a particular system design. One of the best known subjective scales for measuring SA is the Situational Awareness Rating Technique (SART) developed by Taylor (1990). The SART allows operators to rate a system or design based on the amount of demand on attentional resources, supply of attentional resources, and understanding of the situation provided (Taylor 1990). Follow on studies of the SART's effectiveness and usefulness found that the rating scale is correlated with performance measures, and when used with performance measures may provide a powerful tool for system design (Selcon & Taylor, 1990). This approach is attractive because it is fairly inexpensive and is easy to administer, however, it may not provide an accurate quantification of situation awareness.

This is because the operators may not know of their own inaccuracies or the information they are unaware of, and therefore they have a limited basis for making a judgement of SA. Another consideration is that the demand on attentional resources and supply of attentional resources categories are more closely associated with the measure of workload. As such, a person's self-ratings may be highly influenced by self-assessments of performance under different workload conditions, which may cause the ratings to be biased by issues outside of the SA construct. It is for this reason that in the current experiment we will evaluate all three of the SART categories, but we will focus on the understanding category as the most valid of the three for measuring SA.

The second direct measure technique, questionnaires, provides an objective assessment of SA by obtaining detailed information about subjective perceptions and then comparing them against reality. A critical consideration when using this technique is deciding when the information should be gathered. Administering the questionnaire posttest may present some problems, because memories of dynamic situation awareness will be less reliable with time. Therefore, posttest administration may reliably capture only the operator SA at the very end of a trial. Presenting the questionnaire while the operator is performing the simulated task overcomes this deficiency, however, it is intrusive in that it may alter SA and task performance. This may occur because responding to the queries during task performance provides an additional secondary task. Another possibility is to freeze the entire simulation at randomly selected times, blank the screens, and then query the operators as to their perceptions of the situation at the time. As an example, Endsley (1987) developed the Situation Awareness Global Assessment Technique (SAGAT), which is a tool that uses temporary freezes of the simulation, during which the subjects are queried about all SA requirements, including Level 1, Level 2, and Level 3 situation awareness. This approach may limit possible biases of attention, because the subjects cannot

prepare for the queries in advance, since they could be queried over almost any aspect of the situation. Considerable care must be taken, however, in the development of the battery of queries to be administered, in order to ensure that all of the SA requirements (Level 1,2,3) are included. There is also an associated disadvantage with this technique, which involves the temporary halt of the simulation.

Because the SART (Taylor, 1990) and SAGAT (Endsley, 1987) are two of the most commonly used SA measures, Endsley, Selcon, Hardiman and Croft (1998) sought to provide a direct comparison of the two measures when used within a display evaluation study. The researchers utilized two different navigation displays, with one display configuration providing visible threat envelopes revealing information concerning pop-up threats and the other configuration not presenting the threat envelopes. In the study, pilots were required to navigate to different waypoints during a low level flight scenario. Pop-up threats appeared during the flight which pilots were required to avoid, while at the same time staying as close to their predetermined flight path as possible. Pilot performance was measured in terms of RMS error from the assigned course and the total time spent inside the threats' launch zone, and SAGAT and SART were administered during freezes which occurred at random times during the threat avoidance task.

Endsley et al. (1998) found that both of the measures contributed sensitivity and diagnosticity regarding the effects of the display concept. The overall SART rating was found to be significantly higher with the threat envelopes than without, a difference which was mainly attributable to differences in subject ratings of the underlying dimension of understanding. On the other hand, results for the SAGAT measures revealed that while the threat envelopes enhanced the pilots SA regarding their own heading and roll attitude, the envelopes actually

decreased the pilots SA regarding the location of threat aircraft and their ability to determine whether the pop-up would be a threat if they maintained their current heading. The researchers conducted a correlation analysis, which revealed that there was no correlation between the SART components (demand on attention, supply of attention, and understanding) and the SAGAT measures. The researchers cautioned that since the subjective SART and objective SAGAT measures were not correlated, some doubt arises as to the validity of the SART as an indication of a person's actual SA. However, the SART was highly correlated with confidence level in SA and subjective rating of performance, which provides the level of a person's perceived quality of SA. This may be important in determining how a person will choose to act on their SA, independent of the actual quality of their SA.

The final direct technique or approach we will describe for measurement of SA is the use of performance measures. This approach is advantageous in that these measures are objective and usually nonintrusive, since simulation computers can be programmed to record specific performance data automatically. Researchers generally agree that global performance measures are not useful for measurement of SA, because assessing the end result of a task reveals little about the situation awareness that occurred throughout the task. A way to avoid this problem is to embed specific tasks within the context of an ongoing scenario that tap the implicit knowledge of the different dimensions of SA. An example of this would be to incorporate a disorienting event that often leads to a loss of SA and assess an individual's ability to determine the present attitude and the desired future attitude following the disorienting event. From such events, an individual's level of SA can be inferred from the nature and timing of choices made in response to the event. Wickens and Haskell (1993) incorporated this technique into a study evaluating a 3D and a 2D navigation display used during microwave landing systems approaches. During the

approaches, the pilots had to fly through several disorienting events, including 5-second wind shears, 5-second display failures, and combined events consisting of a wind shear followed by a display failure after 2 seconds. Pilots were told which type of disturbance to expect at the beginning of the experiment, however, they were not given any information concerning when and where on each path the disturbance events would occur. Wickens and Haskell measured each pilot's flight control accuracy before, during and after the disturbance events, from which they were able to infer which display facilitated quicker and more accurate recovery. Their results suggested that although the 3D display provided superior flight-path tracking accuracy during normal flight, it might hinder performance during the disturbance events. One also needs to keep in mind that, as with developing questionnaires, considerable preplanning must be conducted to ensure a plausible experimental scenario that mimics realistic aspects of the real world.

These descriptions of the various techniques reveal that each has its advantages, but also some related costs. This serves to highlight the point that a multiple technique approach must be taken when trying to measure situation awareness. Rather than focusing on one particular measurement tool, researchers need to use several techniques and then evaluate the degree to which these multiple measures tend to agree or disagree in regards to how they are affected by a specific display or design condition and its ability to promote situation awareness.

Thus, having defined and discussed local guidance and situation awareness, we will now proceed into a discussion of frames of reference (FOR) and their relevance for electronic map display design, because this is the critical independent variable that we will use to evaluate pilot local guidance ability and the correspondence or congruence of different SA measures. We will first explain different frames of reference and their characteristics. Then we will continue with a

discussion of the design parameters that determine an electronic map display's frame of reference. Finally, we will present previous research that has evaluated electronic map displays using different frames of reference, highlighting those studies that measured local guidance and/or global situation awareness in an aviation context.

### Frame of reference

As discussed earlier, local guidance requires that a pilot have knowledge of his or her current position with regards to the specified ideal flight path, or in simpler terms, he or she needs to know "where am I" at any given moment. This knowledge requires a highly ego-centered frame of reference (ERF), which is characterized as a small scale, forward looking perspective (3D) view of the world (Wickens, 1998). The ERF is typified by what pilots see in their FFOV and is defined in terms of left, right, above, below, and near-far (Wickens, 1998). On the other hand, global situation awareness requires that a pilot have knowledge of potential hazards that are not visible in the FFOV. This involves pilots knowing where these hazards are in a more world-centered frame of reference (WRF), which means that the location of the hazards is always the same independent of the location and movement of the aircraft (Wickens, 1998).

This discussion shows that these two tasks require very different knowledge states in order to perform them successfully. A simple solution for this, if they were independent, discrete tasks, would be to develop two separate displays to support each frame of reference. Unfortunately, the two tasks are often performed concurrently during flight, which means that a pilot would have to switch back and forth between the two displays. This would lead to a high level of mental workload, resulting from the mental transformations required to cognitively integrate the frame of reference information across the two displays. The increased mental workload caused

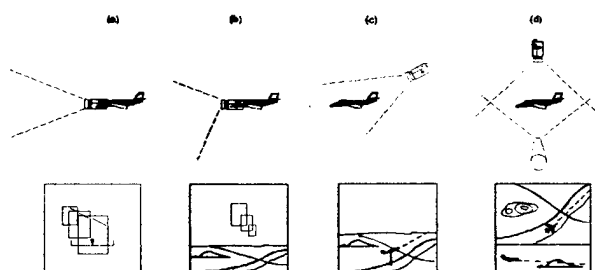
by these mental gymnastics suggests that there needs to be some form of display integration, in order to support both the ERF and WRF within one display.

Researchers have realized that 3D electronic map displays allow for the presentation of an integrated view of these different frames of reference (Olmos, Liang, & Wickens, 1997; Olmos, Wickens, & Chudy, 1998; Wickens & Prevett, 1995; Wickens, Liang, Prevett, & Olmos, 1996). However, depending on a number of design parameters, this presentation can vary dramatically as to the level of ERF and WRF represented. Therefore, we will now transition into a discussion of the parameters that determine a 3D electronic map display's frame of reference.

### *Electronic maps*

In the design of an electronic map, frame of reference is defined by the viewpoint, relative to the momentary FFOV, that is presented to the pilot (Wickens, 1998). As such, the actual frame of reference adopted by a display is a function of three parameters: the location of the viewpoint, the relative motion of the viewpoint, and the attitude of the viewpoint. The location of the viewpoint (represented by cameras) determines the field of view (FOV) that is presented by the electronic map display. When the viewpoint is placed in the aircraft, as shown in panel A and B of Figure 1, an immersed perspective or egocentric FOV is presented, which essentially mimics the pilot's FFOV (Wickens, 1998; Wickens et al., 1998). In contrast, when the viewpoint location is removed from the FFOV, the viewpoint presents an exocentric FOV, which shows the aircraft in the context of its surroundings (see panel C, Figure 1) (Wickens, 1998).

**Figure 1.1:** Four different frames of reference for depicting aircraft navigation information.



The motion of the viewpoint determines whether the FOV presented by the location of the viewpoint translates and rotates with the movement and rotation of the aircraft. This depends on whether or not any single projection parameter, such as azimuth angle, elevation angle, or distance vector, is linked directly to the motion of the aircraft. If any parameter is heading slaved, then it is directly linked to the motion of the aircraft, which means the presented FOV is constantly determined by the momentary direction of travel of the aircraft (Wickens, 1998). In other words, a heading slaved viewpoint results in a track-up map that is always aligned with the aircraft's direction of travel and corresponds to a pilot's ERF. On the other hand, if the viewpoint is azimuth fixed, then none of the projection parameters are linked to aircraft motion and the displayed FOV remains fixed. This results in a north-up map, which corresponds to the pilot's WRF. An easy way to envision this is that when viewpoint motion is azimuth fixed, heading and lateral position changes will be indicated on the map display by a movement of the aircraft symbol, while a heading slaved map display will represent these changes by a movement of the full display in the opposite direction (Wickens, 1998).

Viewpoint attitude is the final parameter for determining electronic map display frame of reference. The viewpoint attitude, or its elevation angle, may be slaved to the pitch of the aircraft (Wickens, 1998). This usually occurs when the viewpoint is in an exocentric location where the viewpoint follows the aircraft as if attached to it by a rigid pole, commonly known as a "tethered" view (Wickens & Prevett, 1995; Wickens, 1998). The viewpoint elevation angle may also be fixed at any value between  $0^{\circ}$  and  $-90^{\circ}$ , with the  $-90^{\circ}$  fixed elevation angle resulting in a two-dimensional (2D) planar map. Because this view results in complete compression of graphical information along the vertical axis, this type of view is often coupled with a  $0^{\circ}$  vertical

display in order to present full information about the 3D airspace, to form a co-planar display (see panel D, Figure 1) (Wickens, 1998).

Thus, it can be seen that the particular combination of these design parameters determines how the airspace is displayed to the pilot (Wickens, 1998). Manipulation of these parameters can affect the degree to which the map display depicts ERF and WRF information, such that the FOR can be thought to fall along a continuum of egocentricity. In light of the knowledge required for local guidance and global situation awareness, the frame of reference adopted by an electronic map display can have critical implications concerning the pilot's ability to perform these tasks effectively. We will now discuss previous studies that have evaluated the effects of different FORs adopted by electronic map displays and their effect on a pilot's local guidance ability and/or global situation awareness. This discussion will be divided up into three sections according to the type of displays that result from manipulation of each of the parameters: track-up versus north-up (azimuth motion), egocentric versus exocentric (location), and perspective versus planar (attitude).

#### *Track-up versus north-up viewpoint*

Manipulation of the projection parameters for viewpoint motion determines whether an electronic map display uses a track-up or a north-up format. Traditionally, most maps and navigational charts have been designed in a north-up fashion, which means the world presented to the pilot remains in a fixed position representing the WRF, unless the pilot chooses to rotate it by hand (Williams, Hutchinson, & Wickens, 1996). For flight in any direction besides due north, this type of design requires mental rotation on the part of the pilot in order to align the WRF with the ERF, or what is viewed out of the cockpit. This cognitive demand can be eliminated by the

use of a rotating, or track-up map, which constantly rotates and translates to correspond to the aircrafts location and heading.

The issue of map rotation has received a fair amount of investigation over the past several years with regards to its effects on navigation and situational awareness. Several studies have shown that rotating maps produce greater flight path tracking accuracy and navigational efficiency (Aretz, 1991; Andre, Wickens, Moorman, & Boschelli, 1991; Olmos et al., 1997; Rate & Wickens, 1993; Wickens et al., 1996). This is because north-up maps impose resource, or workload, costs during navigation, which translates into performance decrements. When a pilot flies a southerly heading using a fixed map, landmarks displayed to the left on the map are actually to the right in the view of the world, which requires the pilot to perform time and effort consuming mental rotation to bring the two views into congruence (Aretz, 1991; Olmos et al., 1997; Rate & Wickens, 1993; Wickens et al., 1996). Therefore, track-up maps are preferred when flight profiles require rapid decisions regarding lateral turns (Wickens et al., 1996).

The advantages of rotating maps have not been as clear cut, however, concerning situational awareness. Some studies have found that north-up maps better support the learning of an environment (Aretz, 1991; Barfield et al., 1995; Williams, Wickens, & Hutchinson, 1996). In each of these studies, a post-trial map reconstruction task was utilized which required the subject to recall as many landmarks and flight path characteristics as possible. Results revealed that the north-up map resulted in better subject performance for this task. The researchers concluded that this was because the landmarks and features of the world are presented in a constant frame of reference (i.e., WRF), which allows the user to more quickly create a mental map of the surroundings. This mental map represents global spatial knowledge that results in increased situation awareness, particularly global situation awareness.

On the other hand, other studies have not found north-up maps to be more advantageous for situational awareness. A study conducted by Rate and Wickens (1993) evaluated the effects of map display rotation on situational awareness in landing approaches. Measurement of situation awareness was assessed in terms of error and response latency to probed questions regarding terrain features. Their results suggested there were no significant differences between the north-up and track-up displays in terms of situation awareness. Wickens et al. (1996) conducted an experiment to extend the work done by Rate and Wickens (1993), which looked at pilot performance during terminal area navigation. They used a position report task, a frozen-screen test, and a map reconstruction task to assess the level of global situation awareness. Results for this study revealed that the rotating, track-up map display was not detrimental to the situation awareness tasks. Wickens et al. (1996) concluded that using a north-up map while actively flying might result in mental rotation workload costs that neutralize and thereby eliminate any fixed-map benefits to the long-term retention of environmental structure.

Olmos et al. (1997) utilized the same paradigm as Wickens et al. (1996), however, they incorporated a simulated FFOV to allow pilots the opportunity for direct observation of surrounding terrain, simulating visual meteorological conditions (VMC). They used a position report task, FFOV-map comparison task, direction-indicating task, and map reconstruction as measures of situation awareness during navigation of terminal area approach paths. Overall, results suggested that the track-up map display actually supported better global situation awareness than the north-up map. This was seen by the increased speed at which pilots were able to identify a target's location in the FFOV when using the track-up map, an advantage which they attributed to the consistent ERF shared between the FFOV and the rotating map. This ability to ascertain a target's location is essential to maintaining maximum hazard awareness.

Also, this study found no evidence supporting previous research findings that the fixed map supported better long-term retention of terrain features.

### *Egocentric versus exocentric viewpoint*

As discussed previously, the location of the viewpoint determines whether an electronic map display presents an immersed FOV (panel A and B, Figure 1) or an exocentric FOV (panel B, Figure 1). Many researchers believe that these two different 3D viewpoints are as different from each other as both are from a 2D display (Olmos et al., 1998). Several studies have compared these two viewpoints, sometimes along with a comparison of a 2D coplanar map.

Barfield, Rosenberg, & Furness (1995) compared an egocentric and an exocentric electronic map display in the context of a simulated F-16 scenario. The authors measured the subjects' deviations from the flight path and found that the immersed display resulted in superior local guidance performance, which they attributed to the compatibility of motion between the simulated out-the-window view and the immersed display. Global situation awareness was also measured by using a posttest spatial reconstruction task that required the subjects to locate the position of each target on a computer generated top-down map of the flight scene. In contrast to local guidance, the results for this task revealed far better performance by the exocentric display. The authors concluded that this advantage resulted from the static compatibility that occurred between the exocentric display and the target positioning task planview map.

Another study by Wickens and Prevett (1995) compared five different map display viewpoints, consisting of an immersed display with an expanded geometric field of view (GFOV), three different exocentric displays (varied by distance vector lengths), and a 2D coplanar display. Examination of flightpath deviations revealed that the immersed display

resulted in superior horizontal and vertical flight performance. The researchers also measured global situation awareness by incorporating a freeze into the scenario to query the subjects as to their awareness of the situation at that moment, and by administering a posttest map reconstruction task. Results for the freeze task revealed that performance for the egocentric display was substantially worse than the other map display types, while the map reconstruction task did not reveal any significant differences between the display types. The results for the freeze/query measure were attributed, in part, to the distortion of the displayed world required to bring all objects in front of the aircraft into the immersive view (i.e., distortion caused by the expanded GFOV), while the map reconstruction task results were connected to the possibility that terrain information was only needed to sustain ongoing situation awareness, and therefore it was not encoded into long-term memory.

Olmos et al. (1998) compared immersed, exocentric, and 2D coplanar map displays in an experiment that required subjects to navigate through a simulated airspace populated by waypoints, hazards, and traffic. As with Barfield et al. (1995) and Wickens and Prevett (1995), the researchers found that the immersed display proved to be superior for local guidance. Olmos et al. (1998) also incorporated a number of global situation awareness measures, to include actual contact with surrounding terrain or hazards, verbal report of external threats, and an implicit measure resulting from pop-up conflicts. Results from these measures were somewhat ambiguous, revealing that performance with the immersed display (which had also incorporated a small exocentric hazard display for global situation awareness) suffered from visual attention allocation problems. Those problems were attributed to the more "compelling" and information rich immersed view drawing attention away from the hazard display. Also, both of the 3D

displays suffered in regard to hazard awareness, because of problems associated with estimating the height of approaching hazards.

Thus, there appears to be a trade-off with respects to the benefits of the egocentric viewpoint. While immersed displays provide superior performance for local guidance and navigation requirements, they suffer in their ability to provide sufficient global situation awareness.

### *Perspective versus planar viewpoint*

The attitude, or elevation angle, of the viewpoint determines whether the map display will have a perspective view or a planar view. As discussed before, the elevation angle may be presented from various vertical perspectives between the range of  $0^{\circ}$  and  $-90^{\circ}$ , with the planar view (panel D, Figure 1) occurring when the viewpoint elevation angle is at  $-90^{\circ}$ . Because this view results in the total loss of vertical resolution, this 2D "God's eye" view is often coupled with a  $0^{\circ}$  vertical display, resulting in a co-planar view display (Wickens, 1998). There have been several studies that have evaluated how these two types of views compare.

Merwin, O'Brien and Wickens (1997) compared exocentric 3D and 2D coplanar versions of a cockpit display of traffic information (CDTI), that involved pilots flying a series of conflict avoidance maneuvers. The researchers measured the pilot's ability to quickly fly to a distant waypoint while avoiding actual or predicted traffic conflicts (analogous to hazard awareness). The results indicated a consistent advantage for the 2D coplanar display over the exocentric 3D format in supporting traffic avoidance maneuvers. These results were attributable to the ambiguity with which the exocentric display depicts position and separation along the line of sight (LOS).

In the study by Rate and Wickens (1993) requiring pilots to fly a curved approach to landing in a terminal area, information was rendered on either an integrated, exocentric 3D display or a 2D co-planar display. The results of this study revealed that the 2D display was superior to the 3D view in terms of both lateral and vertical tracking. This result was attributed in part to the ambiguity of depicting spatial information on a 3D display. Measurement of global situation awareness was assessed in terms of error and response latency to probed questions regarding terrain features. This measure of hazard (terrain) awareness provided ambiguous results as to which display viewpoint provided superior GSA.

Wickens et al. (1996) carried out an experiment using a similar paradigm to that of Rate and Wickens (1993), however, they improved some of the deficiencies in the presentation of altitude on the 3D display. Results from this study showed lateral tracking to be equivalent between the two views, and only a small 3D cost in terms of vertical tracking, which showed a trend toward substantial improvement with practice. The authors used a position report task, a frozen-screen test, and a map reconstruction task to assess the level of global situation awareness. Again, the global awareness measures revealed ambiguous results, with the 3D display allowing for faster responses to the global awareness questions, but the 2D display providing more accurate responses. Results from the map reconstruction task revealed a marginally significant difference between drawings based upon the two maps, with maps drawn on the basis of 2D map exposure containing slightly more accurate placement of terrain features, as might be anticipated given the LOS ambiguity of the 3D display.

The Wickens and Prevett (1995) study discussed above also compared 3D exocentric displays with a 2D coplanar display. In this study, the three exocentric displays varied with regards to the length of the viewing distance vector, with the three different lengths being 3,000 m, 7,500 m,

and 21,000 m. Tracking performance results revealed that horizontal tracking suffered with the far exocentric display (i.e., 21,000 m viewing distance vector), while vertical tracking suffered with use of the close exocentric display (i.e., 3,000 m). Hence the middle distance (7,500 m) tended to be optimal. The researchers also measured global situation awareness by incorporating a freeze into the scenario to query the subjects as to their awareness of the situation at that moment (broken down into world-referenced questions and ego-referenced questions), and by administering a posttest map reconstruction task. Results for the map reconstruction measure did not reveal any significant differences between the different types of map displays, while the query questions provided ambiguous results. Performance with the coplanar display was slower and less accurate for the world-referenced questions, but more accurate for the ego-referenced questions.

Another study that compared an exocentric 3D display with a 2D coplanar display was the Olmos et al. (1998) study discussed above, where subjects flew through a simulated airspace populated by waypoints, hazards, and traffic. Results revealed that both the exocentric and the 2D displays suffered in terms of navigation support, however, each for a different reason. The exocentric display suffered ambiguity in estimating ownship position and heading, while the 2D display suffered from the costs of lateral and vertical cross panel integration. In depth analyses revealed differential costs for the coplanar and exocentric displays on vertical versus lateral flight legs, with the coplanar display suffering the greatest costs on legs involving only vertical maneuvers and the exocentric display suffering the greatest costs on lateral maneuvering legs. A number of global situation awareness measures were also incorporated into this study, to include verbal report of external threats, actual contact with surrounding terrain or hazards, and an implicit measure resulting from pop-up conflicts. Comparison of these GSA measures between

the exocentric and 2D displays revealed ambiguous results similar to those found by Wickens et al. (1996), with the exocentric display providing quicker response times for the verbal report of external threats and reduced time spent in contact with hazard volumes, while the 2D coplanar display provided more accurate judgement of the altitude of pop-up conflicts.

Olmos et al. (1997) reexamined the variables manipulated by Wickens et al. (1996), however they incorporated a FFOV to support the pilot's navigational task, which simulated VMC. In contrast to the results of previous studies (Rate & Wickens, 1993; Wickens et al. 1996), this study did not observe a cost for vertical tracking with the 3D display. In addition, the authors found a slight trend toward better lateral tracking performance with the 3D display as compared to the coplanar display. They attributed these results to a reduced scanning cost for the 3D display when transitioning between the FFOV and the electronic map, to an adherence to Roscoe's (1968) principle of pictorial realism, and to further augmentations to improve the altitude coding on the 3D display. However, the 3D advantage in terms of flight control was not replicated for their global situation awareness measures of a position report task, a FFOV-map comparison task, a direction-indicating task, and map reconstruction task. The FFOV-map comparison task and altitude probes within the position report task revealed significant differences between the two views, and both found the 2D format to be superior in terms of global situational awareness.

One of the reasons why there may be ambiguity concerning which of these two displays provides the best local guidance and global situation awareness support may be because of the different costs associated with each type of display. Exocentric displays are beneficial in that they reduce the need for visual scanning between panels, they reduce the need for mental integration, and they present a 3D "picture" that looks like the real visual scene viewed by the

pilot (Wickens et al., 1996). However, against these potential advantages are some related costs. Exocentric displays typically create some ambiguity regarding the precise position of an object along the line of sight, they typically lose resolution in depicting motion or position along the viewing axis, and imprecise matching between the viewing distance between the display surface and the pilot's eyes may result in distortion in perceived location of objects (Merwin et al., 1997; McGreevy & Ellis, 1986; Olmos et al., 1998; Wickens et al., 1996). Therefore, the relative value of either type of display may be determined by the need to perform certain tasks that may or may not impose the associated costs of each.

Besides the type of tasks that pilots are required to perform, the altitude of flight may also determine which display is more effective. This dependency was revealed by a recent study by Hickox and Wickens (1997), that evaluated the effect of disparity between a range of FFOV images from different elevation angles and an exocentric map display also presented from different elevation angles. The map display and the FFOV were simultaneously presented to the subjects, and a same/different comparison task was used to determine the effect of varying degrees of elevation angle disparity between the FFOV and the exocentric map display. Response times for the comparison task revealed that small disparities between the FFOV and map display, across most map display elevation angles, resulted in negligible costs, however, larger disparities resulted in the cost of a particular disparity being amplified. These results suggest that the advantage for a tethered exocentric display, where the camera elevation angle is slaved to the aircraft's pitch or attitude relative to a 2D display, may increase at lower flight levels when the pilot's view of the terrain is more forward looking.

An experiment similar to Hickox and Wickens (1997) was conducted by Schreiber, Wickens, Renner, Alton, and Hickox (1998), which also utilized static 3D images for both the map and the

FFOV, with several different elevation angles used for both map and FFOV images. However, instead of presenting the map display and FFOV simultaneously, the subjects were presented with the 3D-map image for 5 seconds after which the computer would switch to the FFOV picture. As soon as the FFOV image was displayed, the subjects were asked to judge whether the map and the FFOV matched or mismatched, with both response time and accuracy recorded. The researchers found that response time increased and accuracy of performance decreased as the foreshortening disparity increased, where foreshortening disparity captures the effect of different amounts of elevation angular disparity at different map angles. The researchers concluded that at low approach angles (i.e., low altitude flight), small to medium levels of elevation angular disparity result in large foreshortening disparities, which correspond to decreased performance.

This section has shown that there are many different factors that may influence the effectiveness of displays using either exocentric viewpoints or 2D viewpoints, with the type of task and altitude of flight particularly affecting their usefulness. It is also worth noting the continued ambiguous findings regarding which of the two display viewpoints best facilitates situation awareness.

#### Present research

In summary, the literature has shown that there are several different parameters whose influences must be evaluated when determining which frame of reference an electronic map display should adopt. These parameters determine how much ERF and WRF information a particular map display presents to the pilot. The level of ERF and WRF knowledge that the map display facilitates has a direct influence on a pilot's ability to perform local guidance tasks and

achieve and maintain global situation awareness. We will now summarize the previous research findings and highlight particular concerns for the low altitude rotorcraft environment.

Previous research has shown the utility of a track-up map format. Several studies have shown that rotating maps produce greater flight path tracking accuracy and navigational efficiency (Aretz, 1991; Andre, Wickens, Moorman, & Boschelli, 1991; Olmos et al., 1997; Rate & Wickens, 1993; Wickens et al., 1996). This characteristic makes track-up maps preferable when flight profiles require rapid decisions regarding lateral turns (Wickens et al., 1996). Referring back to Flach and Warren's (1995) precision and responsiveness requirements for low altitude flight, this research shows that a track-up map format seems appropriate for use in the rotorcraft context. Also, recent work by Olmos et al. (1997) has shown that a track-up map display may actually improve hazard awareness and global situation awareness when used during VMC. Since over 93% of rotorcraft missions occur during VMC, a rotating map would seem to be desirable for rotorcraft operations. Therefore, considering the effectiveness of the track-up format to support both local guidance and global situation awareness, we chose to employ a rotating map display for this study.

The literature does not show the same degree of agreement concerning the use of immersed, exocentric, or 2D coplanar map viewpoints and their effect on local guidance and GSA. There seems to be a trade-off between the different types of displays and the level of local guidance and GSA each offers. The immersed display has been shown to offer superior local guidance performance (Barfield et al., 1995; Olmos et al., 1998; Wickens & Prevett, 1995), however it also suffers from a "keyhole" view of the world, which makes obtaining sufficient GSA difficult (Wickens, 1998; Woods, 1984). Efforts to reduce this "keyhole" cost by expanding the GFOV results in a distorted view of the displayed world which in itself makes obtaining GSA difficult

(Wickens & Prevett, 1995). The differences between the exocentric and 2D coplanar formats are more subtle and depend on a tradeoff between the costs imposed by each. The coplanar format imposes visual scanning requirements and mental transformations to cognitively integrate information across the lateral and vertical displays (Wickens et al., 1996), while the exocentric format suffers from a loss of resolution and ambiguity and imprecision in judgements along the line of sight (Wickens et al., 1996). The relative importance of these costs, and thus the value of either type of display format, may be determined by the cost of visual scanning requirements versus the need for dimensional integration within the task and the need for precise judgements along axes that are parallel to the viewing axis within the 3D display (Wickens, 1998). Therefore, it is somewhat unclear as to which of these three displays most effectively supports both local guidance and global situation awareness (Wickens, 1998).

This uncertainty concerning which display is most effective for providing both local guidance and global situation awareness is an important consideration if electronic map displays are to be utilized. However, there are many questions that the previous research does not address in regards to the use of electronic map displays in a rotorcraft cockpit. Most of the research on electronic map displays has been conducted in fixed wing aircraft scenarios where the pilots are flying high over the terrain and do not have to worry about terrain or obstacle strikes (Barfield et al., 1995; Olmos et al., 1997; Merwin et al., 1997; Rate & Wickens, 1993; Wickens & Prevett, 1995; Wickens et al., 1996). As mentioned in the introduction, the versatility of the helicopter often results in it performing its missions at very low altitudes. Therefore, research needs to be conducted in a low altitude rotorcraft specific context to see if the conclusions drawn from these previous studies generalize to very low altitude flight.

Another shortcoming of the previous research is that, with the exception of Olmos et al. (1997), the majority of the studies investigating FOR have been done in instrument flight rules scenarios in which no FFOV was presented. Also, even though Olmos et al. (1997) incorporated a FFOV into their study, they only evaluated 2D coplanar and 3D exocentric displays. Recent research by Hickox and Wickens (1997) suggests that a 3D immersed display may be particularly advantageous for very low altitude flights. Therefore, since many rotorcraft missions occur at very low altitudes during VMC, it seems appropriate, and necessary, to evaluate the effects that immersed, exocentric, and 2D displays have on local guidance and GSA during low altitude flights when a FFOV is present.

Furthermore, although many studies have shown that an immersed display suffers from a "keyhole" view of the world, which makes obtaining sufficient GSA difficult (Wickens & Prevett, 1995; Wickens, 1998), the tradeoff between exocentric and 2D displays in terms of GSA has remained ambiguous (Rate & Wickens, 1993; Olmos et al., 1998; Wickens et al., 1996). This ambiguity suggests that more research needs to be conducted in this area to try and resolve the uncertainty that exists as to which of the two displays provides the best GSA. Finally, even though many of the cited studies in the FOR section used SAGAT-like measures of GSA, none of them utilized the SART (Taylor, 1990) or implicit performance measures. These two GSA measures need to be evaluated in regards to how effectively they measure the level of GSA facilitated by the different types of electronic map displays when used in a low altitude scenario.

Based on these research questions, the present study will evaluate pilot performance using an immersed, exocentric, or 2D display at two different altitudes while flying with a simulated FFOV through multiple rotorcraft-specific scenarios that incorporate numerous man-made and natural hazards. Pilot performance will be assessed by measures of local guidance ability and

global situation awareness. The simulation computers will be able to measure local guidance ability as the deviations from the defined flight path for each mission. Also, we will utilize three measures of GSA, since several different measures need to be utilized to evaluate pilot GSA, and then evaluated as to the degree to which they tend to agree or disagree in regards to a specific display's ability to promote situation awareness (Endsley, 1996). Based on Endsley's (1996) review of possible measurement techniques, we chose to incorporate three different measures of GSA, to include: 1) an implicit performance measure, achieved by programming situations into the scenarios (i.e., crosswinds during hover) that allowed us to infer the subjects level of GSA, 2) a subjective measure, in this case the SART (Taylor, 1990), and 3) a freezing technique, similar to SAGAT (Endsley, 1987), which evaluated the pilots knowledge level of the 3D airspace.

Considering the independent variables being manipulated, our dependent measures, and the previous research, we developed three hypotheses for this study. The first hypothesis is that the egocentric display will provide the best local guidance performance, especially during the low altitude scenarios as the display becomes more congruent with the FFOV (Barfield et al., 1995; Olmos et al., 1998; Wickens & Prevett, 1995). However, we feel the exocentric display will provide equivalent performance during the low altitude flight, because it will also provide a viewing perspective that is fairly congruent with the pilot's direct view of the forward terrain (Hickox & Wickens, 1997). The second hypothesis is that the exocentric display will provide the best performance on the global situation awareness measures. We believe this advantage will result because the egocentric display suffers from a "keyhole" view of the world, which is poor for obtaining GSA (Wickens, 1998, Woods, 1984). Also, because of the need to cross check between the FFOV and the map display, we feel the fairly congruent view of the FFOV provided by the exocentric display will outweigh its associated costs, which will result in better

performance than the 2D display. Finally, our third hypothesis is that the SART (Taylor, 1990) will be a poor measure of the actual level of GSA achieved by the pilots. We feel this problem will result because the pilots may have a hard time determining their own inaccuracies or judging information that they are not aware of, and therefore they will have a limited basis for making a judgement of GSA with this measure (Endsley, 1996; Endsley et al., 1998). As to the GSA measures, there is considerable variability among researchers as to their recommendations regarding which measures should be used, therefore, a further goal of the present study will be to evaluate the degree to which the different measures agree or disagree with regards to the ability of the different displays to facilitate global situation awareness.

## METHODS

### Subjects

Eighteen students enrolled in or teaching flight classes for the University of Illinois Institute of Aviation participated in the experiment, with the subjects ranging from 20 to 35 years of age (mean=22.5). All subjects were pilots with at least a private license and some instrument time, with a range of flight time from 145 to 3250 hours (mean=433). Excluding the one subject with 3250 flight hours reduced the range of flight time from 145 to 600 hours (mean=267). All subjects received the same instructions (see Appendix A) and were paid \$6.00 per hour for their participation. An additional \$20.00 bonus was awarded to the top performer and two \$10.00 bonuses were awarded to the two next best performers. The winners of the bonus money were determined post-experiment by rank-ordering each subject's performance on several of the performance measures and then averaging across the ranks for an overall score for each subject.

### Apparatus

The study was conducted on an Evans and Sutherland (EandS) SPX 500T image generator driving two Electrohome ECP 3000 color projectors, and a Silicon Graphics IRIS 4D-70GT workstation driving a 44-cm diagonal color monitor. The EandS was used to display the forward field of view to the subjects to simulate visual navigation. Two projection screens, each measuring 228.6 cm vertically and 304.8 cm horizontally, were set at an angle of 115° to each other. One screen was located 300 cm directly in front of the participant and the other was offset to the left side, providing a continuous 38° vertical by 112° horizontal field of view. The scene detail of the EandS was a relatively realistic depiction of mountainous terrain, viewed on a hazy

day and from an elevation and azimuth angle dependent on the pilot's momentary position and orientation with the world. Update rate for the EandS system was 50 Hz.

The IRIS workstation was used to display the electronic maps during the scenarios, and it was located directly in front of the participants such that it did not interfere with the participants' view of the EandS projector screen. The workstation depicted an attitude-direction indicator (ADI), a compass during defined periods of the scenario, speed, on-screen heading and an altitude display, which showed altitude above sea level (see Figure x). The view on the IRIS map was schematic in appearance and was depicted from a fixed elevation angle, which varied with experimental condition, and azimuth angle as described in more detail later. The screen update rate for the IRIS display was approximately 5 Hz.

A Microsoft Sidewinder 3D Pro joystick was attached to the right arm of the participant's chair, which allowed for different control inputs and dynamics according to whether the participant was in forward flight mode or hover mode. The paradigm for this study was that the aircraft was considered in hover mode only when the airspeed equaled zero. The "china hat" on the joystick controlled airspeed, and therefore, it also controlled the transition into and out of hover mode. During forward flight, the joystick controlled the lateral and vertical axes of the aircraft, with standard aviation dynamics. Pushing forward/back on the stick caused a decrease/increase in pitch, with the rate of change of altitude directly controlled by the amount of pitch. Moving the joystick to the right or left made the helicopter roll right or left, respectively, with the roll angle directly proportional to the rate of change of heading. During hover mode, pushing the joystick in any direction caused the helicopter to slew, or translate, in that direction, while maintaining the current aircraft heading. For example, pushing the joystick forward caused the helicopter to translate (move) forward, but did not result in a decrease in pitch.

Likewise, moving the joystick to the right caused the helicopter to translate to the right, but did not result in a rightward roll or a change in heading. The "Twist grip" on the joystick was used during hover mode to change the heading (yaw), with a twist to the left causing the aircraft to turn to the left, or decrease heading, and a twist to the right causing the aircraft to turn to the right, or increase heading. Also, the top side and bottom side buttons allowed the helicopter to ascend or descend during hover mode.

### Simulation database

The flight area used for this study, the Freemont region, was specifically developed for studies at the University of Illinois, and the database was not modeled after any actual geographic region. The Freemont region was rectangular in shape and measured approximately 37.5 nautical miles by 29.5 nautical miles. Also, the region contained a diverse range of terrain types.

### Electronic map displays

There were three different display conditions used in the study. In each of the displays, the world remained the same, while the variation affected only the view of the world presented to the subjects. Since a rotating map was desired for the study, the viewpoint rotation was slaved to the aircraft for all of the display conditions. The following descriptions define the different conditions in greater detail.

The egocentric display, as seen in Figure 2.1a on page 44, was presented from the perspective of the subject sitting in the pilot's seat. The field of view (FOV) was set at  $45^{\circ}$  in the horizontal

and  $36^\circ$  in the vertical. Also, since the viewpoint location was positioned within the aircraft, azimuth angle and elevation angle were zero.

The exocentric display (see Figure 2.1b, page 44) was presented from the perspective of the subject viewing the aircraft from above and behind. The azimuth angle for this display was set at  $0^\circ$ , or directly behind the aircraft, and the elevation angle was set at 45 degrees. The distance from the viewpoint to the aircraft was 31,000 feet, and the FOV for this display was  $45^\circ$  in the horizontal and  $36^\circ$  in the vertical.

The planar display (see Figure 2.1c, page 45) was presented from the perspective of the subject looking directly down on the aircraft. The elevation angle was set at  $-90^\circ$ , which caused complete compression along the vertical axis, and the azimuth angle was set at  $0^\circ$ .

### Experimental design

This experiment manipulated two variables and was carried out using a 3 x 2 block, within subjects design. The variables are:

1. 3D egocentric versus 3D exocentric versus 2D planar, and
2. Low altitude flight (200 ft) versus high altitude flight (1000 ft).

All participants flew both a low altitude and a high altitude scenario with each of the three display types (egocentric, exocentric, 2D), for a total of six missions. The display ordering was blocked and allowed for both a low altitude and a high altitude scenario to be flown within a given display type. Subjects were assigned to one of six possible groups, shown in Table 2.1, which were defined by the ordering of display type presentation blocks and low altitude missions (paths 1,2,3) and high altitude missions (paths 4,5,6) presentation. The ordering of the display type blocks and low and high altitude scenarios was counterbalanced across groups.

Group	Practice			Scored Scenarios					
	1	2	3	1	2	3	4	5	6
	Full	2min	2min	Map/Path	Map/Path	Map/Path	Map/Path	Map/Path	Map/Path
1	2D	Exocentric	Egocentric	Egocentric/4	Egocentric/1	Exocentric/2	Exocentric/5	2D/6	2D/3
2	Exocentric	Egocentric	2D	2D/2	2D/5	Egocentric/6	Egocentric/3	Exocentric/1	Exocentric/4
3	Egocentric	2D	Exocentric	Exocentric/6	Exocentric/3	2D/1	2D/4	Egocentric/5	Egocentric/2
4	Egocentric	Exocentric	2D	2D/1	2D/6	Exocentric/5	Exocentric/2	Egocentric/3	Egocentric/4
5	Exocentric	2D	Egocentric	Egocentric/5	Egocentric/2	2D/3	2D/4	Exocentric/6	Exocentric/1
6	2D	Egocentric	Exocentric	Exocentric/3	Exocentric/4	Egocentric/6	Egocentric/1	2D/2	2D/5

**Table 2.1:** Experimental design used in this study.

### Procedure and task

The trials were broken down into two one-hour sessions during the same day. At the beginning of the first session, the pilots were given written instructions that described the tasks and goals of the experiment. The pilots were then allowed a fifteen-minute practice session, during which they were introduced to the handling and control characteristics of the simulation. This practice session utilized a short path that included all of the unique situations and hazards that the pilot would experience during each trial. The subjects flew the practice path using one type of map display, taking approximately ten-minutes, then had two two-minute segments that exposed the subjects to the other two map display types. Which map display was used for the full practice mission depended on the group to which the subject was assigned (refer to Table 2.1). Subjects were instructed that during the self paced practice session, minimizing the deviations from the flightpath was not the most important issue, but rather the main purpose was familiarization with the unique control and handling characteristics of the simulation and the different types of map displays. However, participants were encouraged to stay on the flight path as much as possible because accuracy was one of the performance measures during the experimental session.

The complete two-hour experimental session consisted of a total of six different seventeen-minute scored scenarios, three of which were flown at a low altitude (200 ft) and three flown at a high altitude (1000 ft). These scenarios are shown graphically in Figure 2.2a-f, starting on page 46. Because terrain was one of the hazards employed in the scenarios, the low and high altitude paths always remained the same. Care was taken in the formulation of the scenarios to ensure that the level of difficulty was consistent regardless of the path. This included making sure that every scenario contained four hover points, seven legs, and three man-made and three natural hazards experienced during forward flight (hover points and hazards described in detail later).

The pilots were told that they were carrying a team of scientists conducting a geological survey for possible oil deposits, which required a very precise flight over the defined path and multiple hover points in order for the scientists on board to map the terrain (see Appendix A for the complete subject instructions). The pilots were instructed to fly the low altitude flights (200 ft) at 70 knots airspeed and the high altitude flights (1000 ft) at 110 knots. This was done to try and capture characteristics of real world helicopter flight, in that pilots usually fly slower the lower they go. They were also instructed to fly each scenario with minimum lateral and vertical deviations from the defined flight path. The required flight path was presented to the pilots by a compass that appeared before the waypoints and at the hover points and was visible for 20 seconds. The compass displayed the heading for the next leg of the scenario to which the pilots were supposed to turn. When the pilots achieved the new heading, which was redundantly displayed by the on-screen heading, they were instructed to maintain that heading until the next waypoint or hover point. If a participant deviated from the specified flight path by more than 500 feet, a command arrow appeared on the map display to direct the pilot back towards the defined route. This was done to ensure that the pilots would come within close proximity of the

hazards, which was needed in order to try and determine the level of global situation awareness attained by the participants.

The hazards encountered during the scenarios were man-made (power lines and towers) and natural (terrain and weather). For the low altitude scenarios, the power lines were placed across the flight path at 200 ft, whereas they were placed across the flight path at 1000 ft for the high altitude scenarios, and the power lines were attached to poles positioned 1500 feet apart. The towers were either 200 or 1000 feet tall, depending on the scenario, and were also placed on or near the flight path. The weather was placed beside or above the flight path and reduced visibility was simulated if the pilot entered the weather. The weather hazards were depicted on the map display, however, they were not visible in the FFOV unless they were entered, in which case FFOV visibility was greatly reduced. The terrain was visible on the electronic map and in the forward field of view (FFOV). All powerlines, weather, and terrain hazards were accurately represented on the map display, however, the towers were not depicted on the map. This was done in an attempt to force the subjects to maintain a visual scan between the electronic map display and the FFOV.

Each scenario also contained four points at which the pilots were directed to hover, which were designed to directly measure the pilot's global situation awareness. Pilots transitioned into hover mode by decreasing the airspeed via the "China hat" on the joystick, and were considered in hover mode when their speed equaled zero. Because of the need to ensure that the pilots hovered at the correct spot, an "X" appeared on the map display at the hover location when the pilots were within 1/2 mile from the point. The "X" disappeared from the map as soon as the pilot entered the hover mode, at which time a compass with a predefined direction was displayed on the map for 20 seconds. The participants were instructed to rotate themselves to point in the

same direction as that indicated on the compass. After 20 seconds, the compass disappeared from the map, which indicated that the pilot needed to transition back into forward flight.

The scenarios were developed such that there were one of four possible situations present at each hover point: 1) hover (H), 2) hover with a cross-wind blowing (HC), 3) hover with a hazard present nearby (HH), and 4) hover with a hazard present nearby and a cross-wind blowing (HHC). These were presented in a fixed order for each scenario. The predefined direction to which the pilots had to rotate was such that the hazards at the hover points were never in the FFOV. Also, the crosswind began blowing exactly five seconds after the pilot entered the hover mode. If a hazard and crosswind were both present at a hover point (HHC), the crosswind always blew the aircraft towards the hazard, while for case HC where there was no hazard present, the crosswind blew the aircraft 180 degrees from the pilots current heading (directly backwards).

#### Performance measures

Several performance measures were collected during each trial in an effort to quantify the level of local guidance and global situation awareness facilitated by the different types of map displays. These measures included flight performance, hazard contacts, direction-indicating tasks, implicit measures, and subjective estimation using the Situational Awareness Rating Technique (SART).

#### *Flight performance*

Lateral and vertical deviations from the specified flight path were measured during each trial. The scenarios were specifically designed to cause the pilots to have to avoid terrain features and

other hazards, but they were instructed to maintain the defined altitude as closely as possible, which meant that they were told to "skim" the terrain and man-made hazards as closely as possible. Therefore, every pilot had to maneuver to avoid these hazards (or if they contacted them the measurement is defined below), but large increases in altitude to avoid the hazards would result in a greater vertical error and lower performance score. Mean absolute error (MAE) was calculated instead of root mean square error, in order to minimize the potential skewing effect from a small percentage of extreme deviations. On all trials, vertical and horizontal errors were sampled at a rate of 2 Hz. Also, for each hover point, the distance between the defined hover point and the actual hover point was measured in feet.

#### *Hazard contacts*

Each scenario's flight path was designed such that it placed hazards directly in the pilot's flight path, which he or she therefore had to navigate to avoid. The number of times a pilot made contact with a hazard and the type of hazard involved were recorded.

#### *Direction-indicating task*

Each scenario contained randomly positioned pink flags that were depicted only on the IRIS map display. At unexpected times during each trial, all of the IRIS map display features, including the pink flags, disappeared (i.e., everything except the map grid disappeared), the scenario was frozen, and the helicopter was automatically placed in hover mode. The pilot's task was to use the joystick to rotate ownship to point directly at the location where they remembered the closest flag. There were two direction-indicating tasks per trial. One of these occurred one mile before the subject reached a flag, and the other occurred one half mile after the subject had

passed a flag. The flags were always visible to the subjects in the exocentric and 2D displays immediately preceding the freeze, however, the flag was never visible in the egocentric display immediately preceding the freeze event after flag task. Deviations were recorded as the angle difference between the heading the pilot rotated to and the exact heading of the closest flag.

### *Implicit measures*

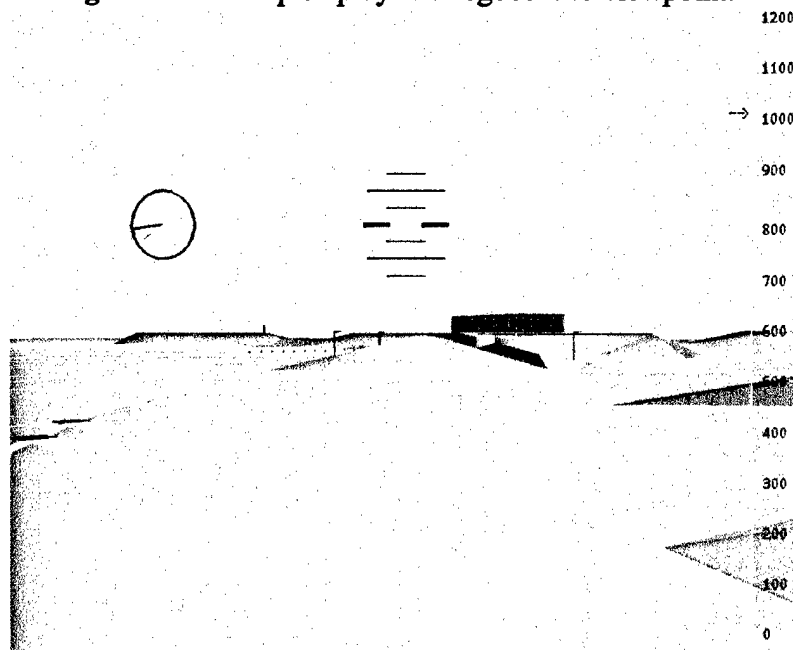
Each trial contained four defined points where pilots were instructed to enter a hover. One of the four hover points included a crosswind which blew the aircraft towards a hazard (HHC). At this hover point, flight control inputs, heading, and position data were continuously sampled (at 5 Hz) throughout the duration of the hover so that the appropriateness of control behavior could be ascertained. The control input data was recorded as deflections of the joystick in the X and Y directions, and the experimenters determined that a deflection value of 2 or greater indicated a meaningful movement. When the control inputs reached the specified thresholds, the simulation computer used the next five samples to calculate a direction vector for the movement. Deviations were recorded as the angle difference between the direction of the crosswind and the direction of the movement vector. Also, the reaction time from the onset of the crosswind until meaningful compensatory input was recorded.

### *Subjective estimation*

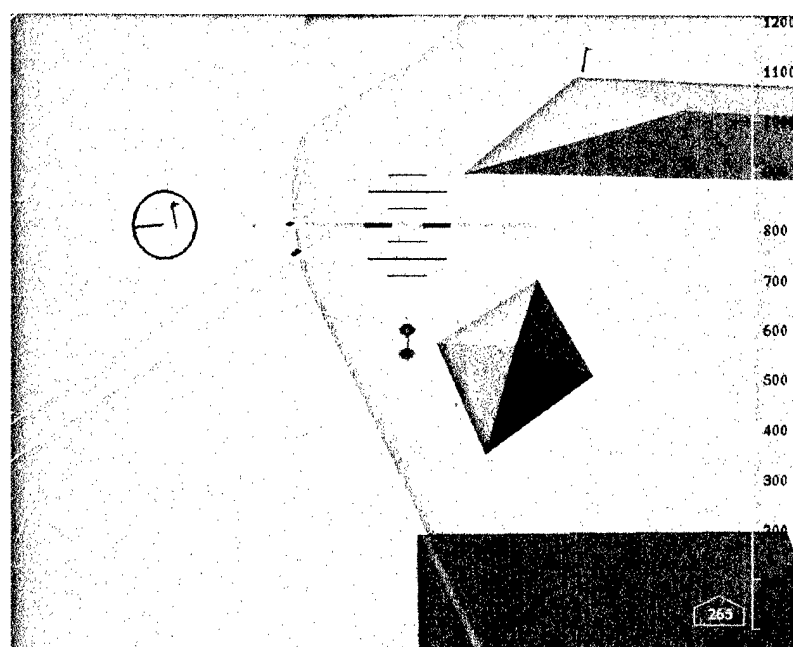
At three minute intervals throughout each scenario, the subjects were asked to verbally rate his or her situation awareness on the three dimensional SART scale. At these points in the scenario, the investigator would say "SART" out loud, which would cue the subjects to provide their ratings. Subjects could refer to an index card attached to the map display monitor that

contained the definitions of the different dimensions of the SART. The dimension was rated on a seven point scale ranging from LOW (1) to HIGH (7).

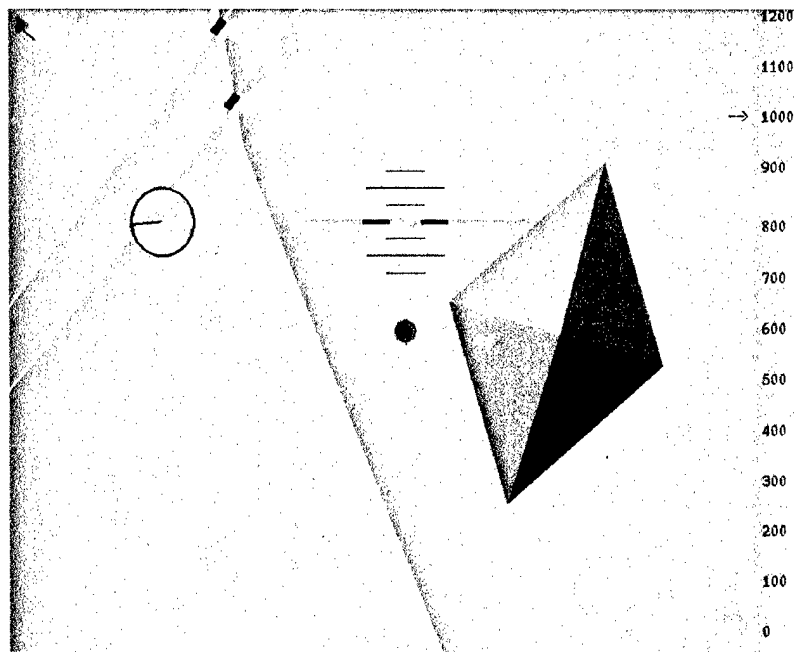
**Figure 2.1a: Map display with egocentric viewpoint.**



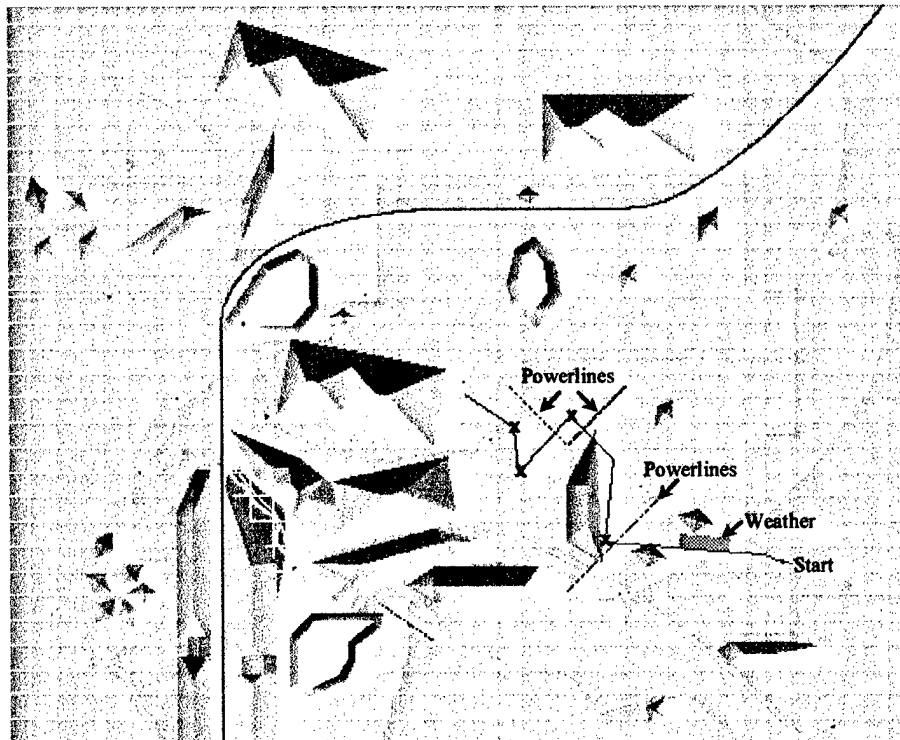
**Figure 2.1b: Map display with exocentric viewpoint.**



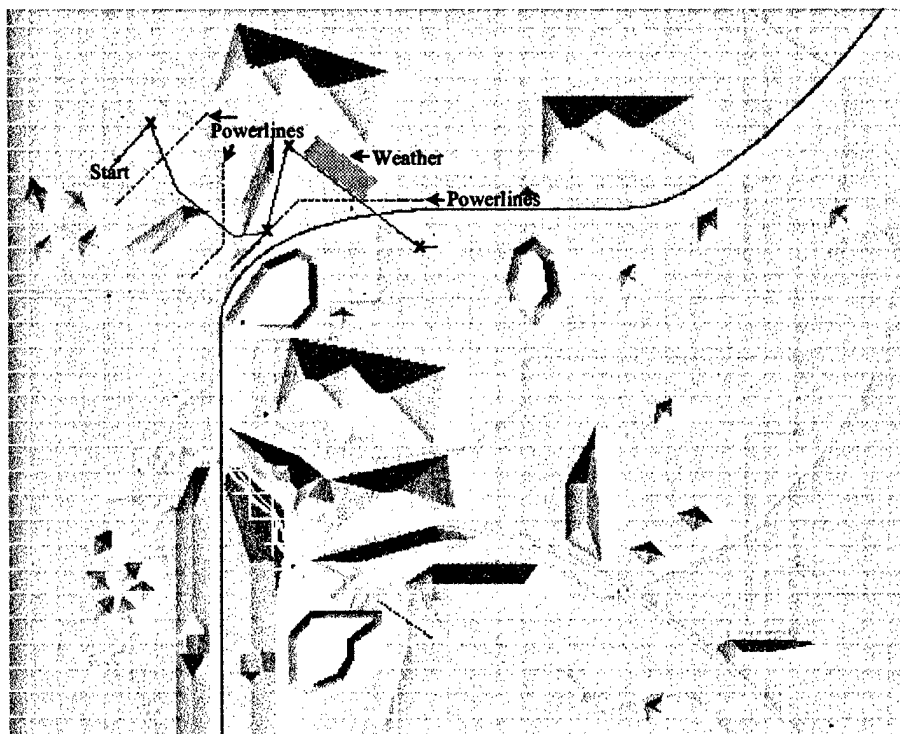
**Figure 2.1c: Map display with planar viewpoint.**



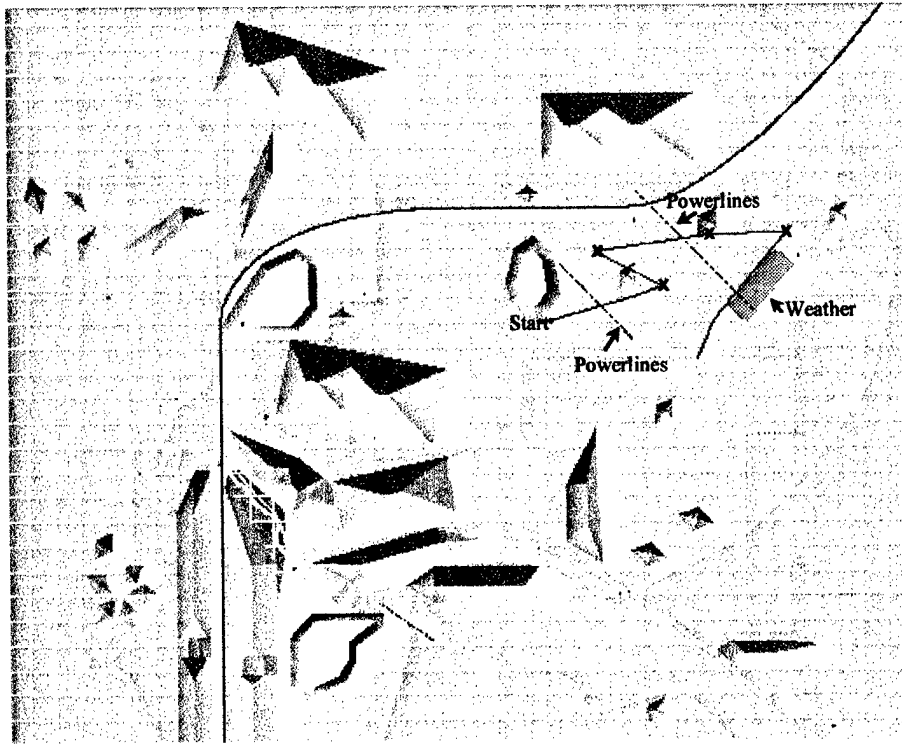
**Figure 2.2a: Path 1 at 200 feet.**



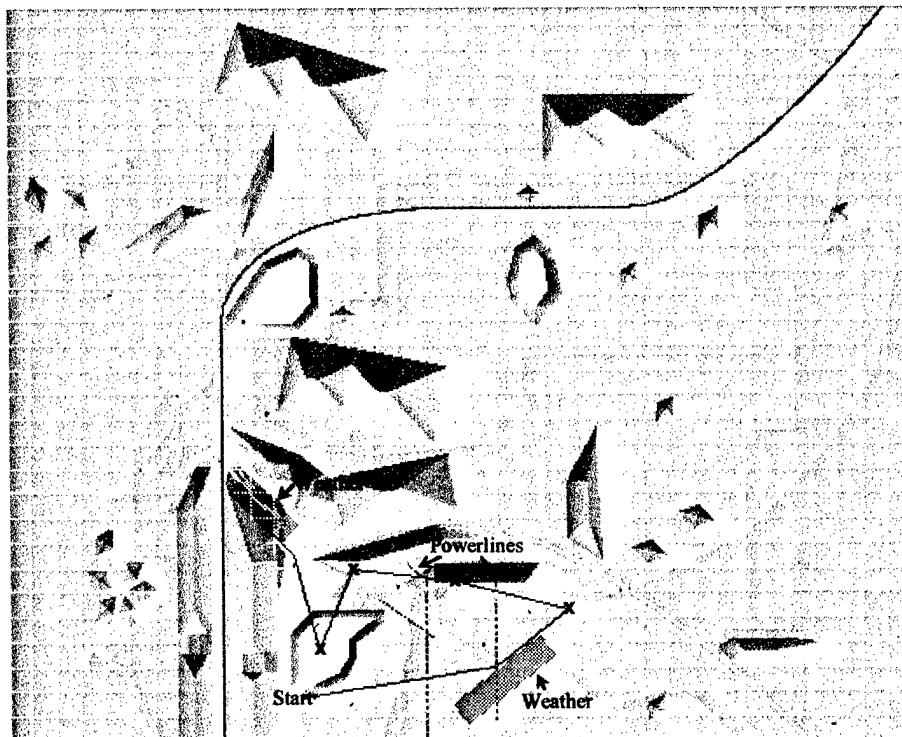
**Figure 2.2b: Path 2 at 200 feet.**



**Figure 2.2c: Path 3 at 200 feet.**



**Figure 2.2d: Path 4 at 1000 feet.**



**Figure 2.2e: Path 5 at 1000 feet.**



**Figure 2.2f: Path 6 at 1000 feet.**



## RESULTS

All statistical analyses were performed using SPSS version 8.0 for Windows™, and the figures were drawn using Microsoft Excel 7.0 for Windows™. All error bars depicted on the figures represent a 95% confidence interval. There were no trial or path effects.

### Flight performance

#### *Horizontal*

Deviation error in terms of horizontal MAE is presented in Figure 3.1a (see page 57). A 3x2 repeated measures ANOVA revealed a significant main effect for altitude level [ $F(1,101)=30.4$ ,  $p<0.001$ ], with greater horizontal errors occurring at the higher (1000 feet) altitude level. There was no significant difference between the three display types [ $F(2, 101)=1.3$ ,  $p=.26$ ], and no significant interaction was revealed between display type and altitude level [ $F(2, 101)=0.2$ ,  $p=0.82$ ].

#### *Vertical*

An analysis similar to the horizontal error analysis was performed on the vertical error data, plotted in Figure 3.1b (see page 57). Again, the analysis revealed a significant main effect for altitude level [ $F(1,101)=27.5$ ,  $p<0.001$ ], with greater vertical errors occurring at the higher altitude level. No significant display type effect [ $F(2, 101)=1.9$ ,  $p=0.16$ ] or display type by altitude level interaction [ $F(2, 101)=0.52$ ,  $p=0.60$ ] was revealed.

### *Stopping distance from hover points*

For each of the hover points, the distance between the defined hover point and the actual point where the subjects stopped to hover was measured in feet, as plotted in Figure 3.1c on page 57. Results from the 3x2 repeated measures ANOVA revealed a significant display type effect [ $F(2, 426)=9.7, p<0.001$ ]. A post hoc Tukey test indicated the 2D viewpoint supported significantly better performance than the egocentric viewpoint or exocentric viewpoint. A significant altitude level effect [ $F(1,426)=15.3, p<0.001$ ], and a significant display type by altitude level interaction [ $F(2, 426)=18.4, p<0.001$ ] were also revealed, the latter indicating that only the exocentric viewpoint provided significantly worse performance at the higher altitude level (1000 feet) than at the lower altitude level (200 feet).

### *Hazard contacts*

#### *Powerlines*

The probability of contacts with powerlines was computed as the actual number of contacts per scenario divided by the number of powerlines present in each scenario. For the low altitude (200 feet) level scenarios, there were three powerlines present, while for the high altitude level scenarios there were two powerline hazards present. A 3x2 repeated measures ANOVA was performed on these contact occurrences, as presented in Figure 3.2a (page 58). There were no significant differences revealed for either the display type [ $F(2, 102)=0.43, p=0.65$ ] or altitude level [ $F(1, 102)=2.60, p=0.11$ ], and there was no significant display type by altitude interaction [ $F(2, 102)=0.90, p=0.41$ ].

### *Towers*

The probability of contacts with towers was computed as the actual number of contacts per scenario divided by the number of towers present in each scenario. For the low altitude (200 feet) level scenarios, there was one tower present, while for the high altitude level scenarios there were two tower hazards present. A 3x2 repeated measures ANOVA was performed on these contact occurrences, presented in Figure 3.2b on page 58. There were no significant differences revealed for display type [ $F(2, 102)=0.00, p=1.00$ ] or altitude level [ $F(1, 102)=1.06, p=0.31$ ], and there was no significant display type by altitude interaction [ $F(2, 102)=0.68, p=0.51$ ].

### *Terrain*

As with the powerlines and towers, the probability of contacts with the terrain was computed as the number of contacts per scenario divided by the number of terrain hazards present in each scenario. The low altitude scenarios contained two terrain hazards while the high altitude scenarios only contained one terrain hazard. It was possible to contact a given terrain feature more than once. The terrain data are plotted in Figure 3.2c (page 59). The 3x2 repeated measures ANOVA revealed a display type effect [ $F(2, 102)=5.2, p=0.007$ ]. A post hoc Tukey test indicated that significantly more terrain collisions occurred with the use of the egocentric viewpoint. Although no significant altitude level effects [ $F(1, 102)=0.98, p=0.32$ ] or display type by altitude level interactions [ $F(2, 102)=1.92, p=0.15$ ] were revealed, further analysis of the egocentric viewpoint data by a paired samples t-test revealed a marginally significant difference between the altitude levels [ $t(17)=-1.84, p=0.08$ ], with more terrain contacts occurring at the higher altitude level.

### *Weather*

For the lower altitude scenarios, there was one weather hazard present, while the higher altitude scenarios contained two weather hazards. The probability of weather contacts was computed as the number of contacts per scenario divided by the number of weather hazards present in each scenario, with the weather contact data presented in Figure 3.2d (page 59). A 3x2 repeated measures ANOVA revealed no significant display type [ $F(2, 102)=0.80, p=0.45$ ] or altitude level effect [ $F(1, 102)=1.06, p=0.31$ ], and there was no significant display type by altitude level interaction [ $F(2, 102)=0.27, p=0.77$ ].

### *Direction-indicating task*

#### *Freeze event before flag*

There was one freeze event per scenario where the freeze occurred one mile before the subject reached the flag. Deviations were recorded as the angle difference between the heading to which the pilot rotated and the exact heading to the closest flag. The angle deviation data are presented in Figure 3.3a (see page 60), with smaller values (i.e., smaller angle differences) indicating better performance. A 3x2 repeated measures ANOVA revealed no significant display type [ $F(2, 102)=1.51, p=0.23$ ] or altitude level effect [ $F(1, 102)=1.41, p=0.24$ ], and there was no significant display type by altitude level interaction [ $F(2, 102)=0.30, p=0.75$ ].

#### *Freeze event after flag*

There was one freeze event per scenario where the freeze occurred one half mile after the subject passed the flag. As with the freeze event before, deviations were recorded as the angle

difference between the heading to which the pilot rotated and the exact heading to the closest flag, again with smaller angle differences indicating better performance. Figure 3.3b (page 60) plots these deviations. A 3x2 repeated measures ANOVA revealed a marginally significant effect for display type [ $F(2, 102)=2.9, p=0.06$ ], with a post hoc Tukey test revealing that the egocentric viewpoint provided the worst performance and the 2D viewpoint supported the best performance. No significant altitude level effect [ $F(1, 102)=1.5, p=0.22$ ]. Also, even though Figure 3.3b appears to show an interaction for the exocentric display, no significant display type by altitude level interaction [ $F(2, 102)=1.45, p=0.24$ ] was revealed.

#### Implicit SA measure

##### *Compensatory control input*

One of the four hover points in each scenario included a crosswind which blew the aircraft towards a hazard (HHC). At this hover point, deviations were recorded as the angle difference between the direction of the compensatory movement vector and the direction of the crosswind, with larger angle differences indicating better performance, as seen in Figure 3.4a (refer to page 61). One of the 18 subjects missed or ignored all of the crosswinds, therefore, this subject was excluded from this analysis. Other subjects also missed or did not provide compensatory control input for the implicit measure at some of the hover points. The frequency with which this occurred for each of the displays and altitude levels is presented in Table 3.1.

	Egocentric	Exocentric	2D
200'	0	1	0
1000'	3	9	9

**Table 3.1:** Number of misses per condition for which no compensatory control input occurred during the implicit measure.

A 3x2 repeated measures ANOVA was performed on the angle differences (excluding the missed cases) and revealed a significant main effect for altitude level [ $F(1,74)=4.4$ ,  $p=0.04$ ], with better performance occurring at the lower altitude level (200 feet), and a marginally significant display type by altitude level interaction [ $F(2, 74)=2.36$ ,  $p=0.10$ ], indicating that only the exocentric viewpoint provided significantly worse performance at the higher altitude level (1000 feet) than at the lower altitude level (200 feet). There was no significant difference between the three display types [ $F(2, 74)=0.39$ ,  $p=0.68$ ]

### *Reaction time*

The reaction time in seconds from the onset of the crosswind at the HHC hover point until meaningful compensatory control input from the subject was recorded. If the subject did not respond to the crosswind (as displayed in Table 3.1), then the reaction time for that case was excluded from the analysis. The reaction times are displayed on page 61 in Figure 3.4b. A 3x2 repeated measures ANOVA revealed a significant altitude level effect [ $F(1, 74)=7.6$ ,  $p=0.007$ ], with greater reaction times occurring at the higher altitude level. There was no significant difference between the display types [ $F(2, 74)=0.07$ ,  $p=0.93$ ], and the display type by altitude level interaction [ $F(2, 74)=0.96$ ,  $p=0.39$ ] was also not significant.

### *Subjective estimation*

Throughout each scenario, the subjects were queried five different times as to their rating on each of the three SART categories (demand on attentional resources, supply of attentional resources and understanding), with each category rated on a seven point scale ranging from LOW (1) to HIGH (7). The five ratings within each category were averaged to provide on

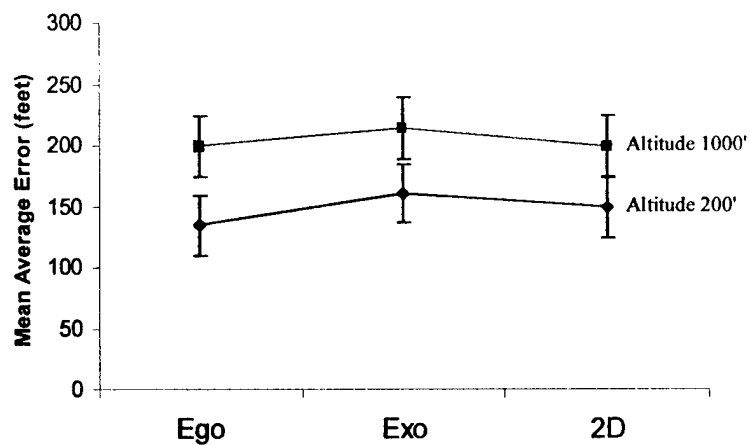
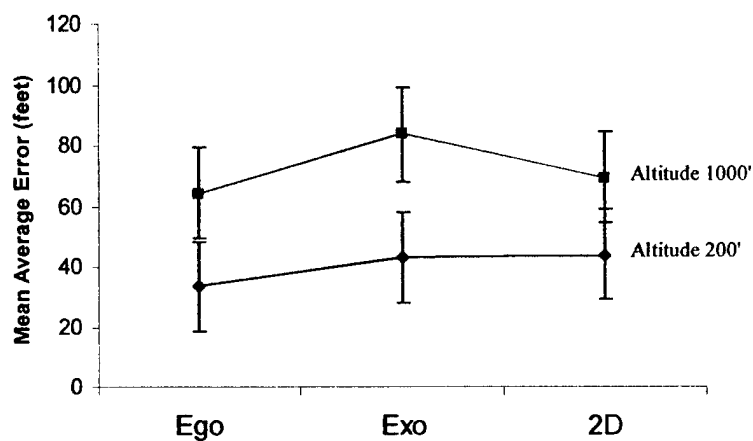
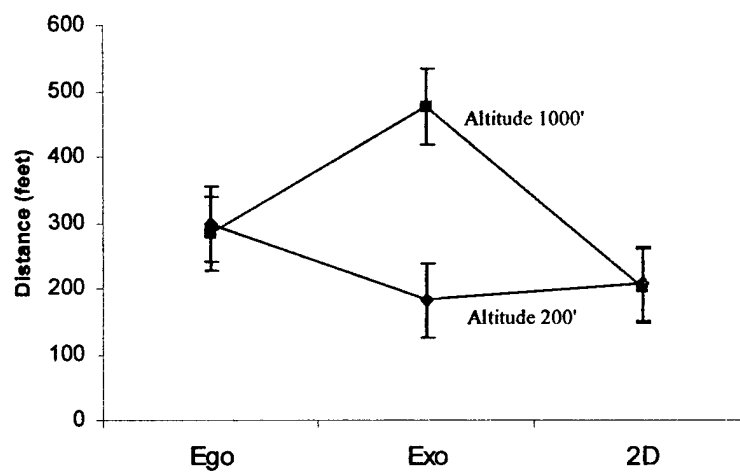
overall rating for each dimension, and a 3x2 repeated measures ANOVA was performed on these average ratings for each of the three categories. Figures 3.5a-3.5c (page 62) display the averaged ratings data. A significant effect of altitude was revealed for demand on attentional resources [ $F(1, 102)=7.3, p=0.008$ ] and supply of attentional resources [ $F(1, 102)=5.2, p=.025$ ]. For both of these categories, a higher average rating was provided during the higher altitude scenarios. A marginally significant altitude effect was revealed for understanding [ $F(1, 102)=3.5, p=0.06$ ], with higher ratings reported during the lower altitude scenarios. No significant display effect ( $[F_{\text{demand}}(2, 102)=0.00, p=1.00]$ ,  $[F_{\text{supply}}(2, 102)=0.09, p=0.91]$ , and  $[F_{\text{understanding}}(2, 102)=1.42, p=0.25]$ ) or display type by altitude level interaction ( $[F_{\text{demand}}(2, 102)=0.08, p=0.92]$ ,  $[F_{\text{supply}}(2, 102)=0.02, p=0.98]$ , and  $[F_{\text{understanding}}(2, 102)=0.79, p=0.46]$ ) was revealed for any of the three SART categories.

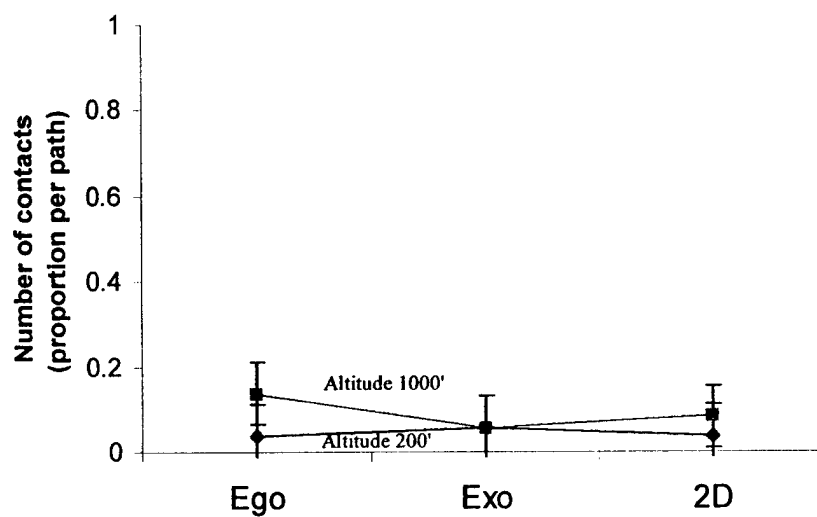
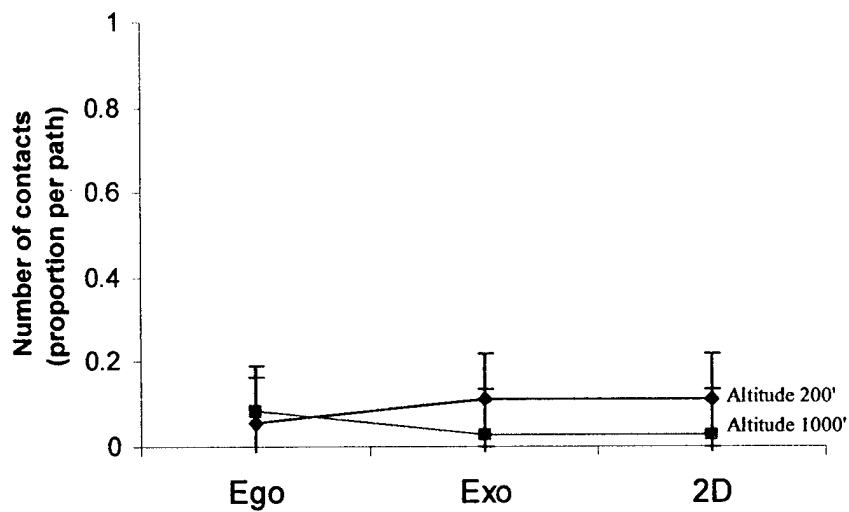
#### Correlation between situation awareness measures

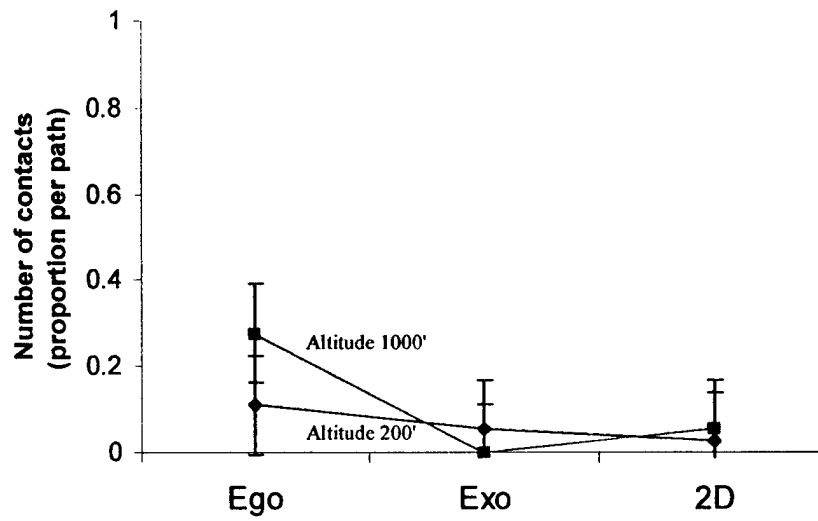
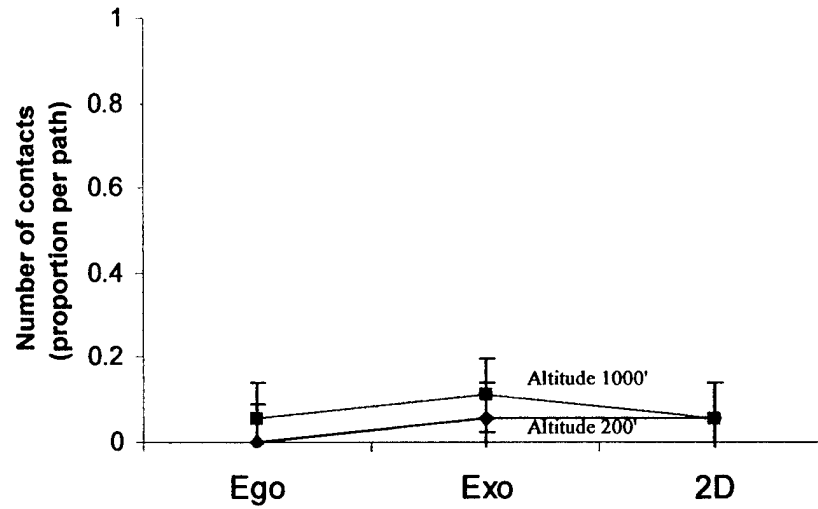
As noted in the introduction, there is considerable variability among researchers as to their recommendations regarding which SA measures should be used. Therefore, we wanted to evaluate the degree to which the different measures we used in this study agreed or disagreed with regards to the ability of different display types and altitudes to facilitate situation awareness. In determining the correlation between the different measures we utilized in the study, we decided not to evaluate two of the SART categories (demand on attentional resources, supply of attentional resources) and the freeze event before the flag task. This was because the two mentioned SART categories are, in effect, a measure of workload and not SA, and the freeze event before the flag task was considered more of a perceptual task than a cognitive task (since the flag was visible in all three display viewpoints at the time of the freeze event). Therefore,

our correlation analysis was performed on what we felt were our most valid measures of SA; the implicit performance measure (compensatory control input), the freeze event after flag task, and the understanding category of the SART. The analysis was done by correlating each measure's average score within each of the six conditions (three display types by two altitude levels) with one another. Also, high scores for the SART and implicit measure represent better performance, whereas lower scores for the freeze event after flag measure represent better performance.

Within each scatterplot representing the correlation between measures, shown in Figure 3.6a-3.6c (refer to page 63-64), each display type is depicted by a different symbol (egocentric=square, exocentric=diamond, and 2D=triangle). Also, those conditions which involve high altitude (1000 feet) missions are denoted by a circle. The correlation obtained between the implicit performance measure and the freeze event after flag task was  $r=0.51$  ( $p=0.30$ ), between the implicit performance measure and SART (understanding) was  $r=0.84$  ( $p=0.03$ ), and between the freeze event after flag task and SART (understanding) was  $r=0.68$  ( $p=0.14$ ). Although only one of the correlations was statistically significant (implicit performance measure to SART understanding), there still appears to be some degree of agreement among the measures, in that all correlations were positive, accounting for at least 50% of the shared variance.

**Figure 3.1a: Lateral tracking error.****Figure 3.1b: Vertical tracking error.****Figure 3.1c: Stopping distance from hoverpoints.**

**Figure 3.2a: Powerline contacts.****Figure 3.2b: Tower contacts.**

**Figure 3.2c: Terrain contacts.****Figure 3.2d: Weather contacts.**

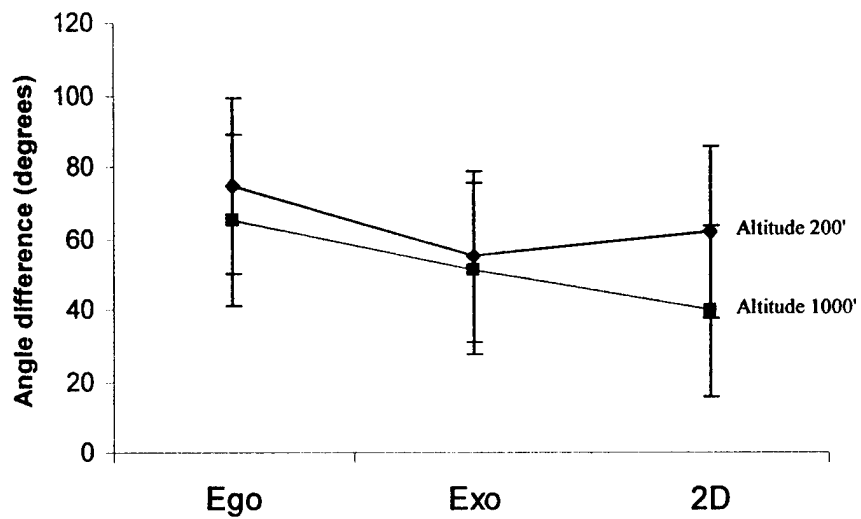
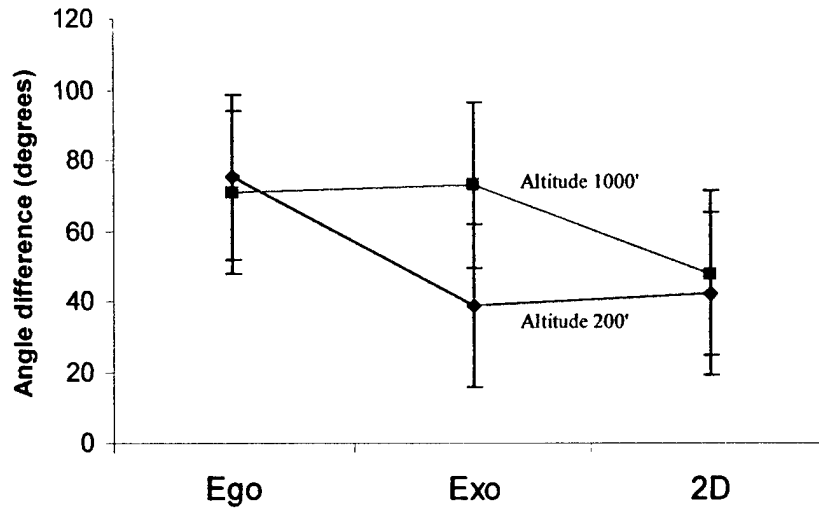
**Figure 3.3a: Freeze event before flag.****Figure 3.3b: Freeze event after flag.**

Figure 3.4a: Compensatory control input at hoverpoint.

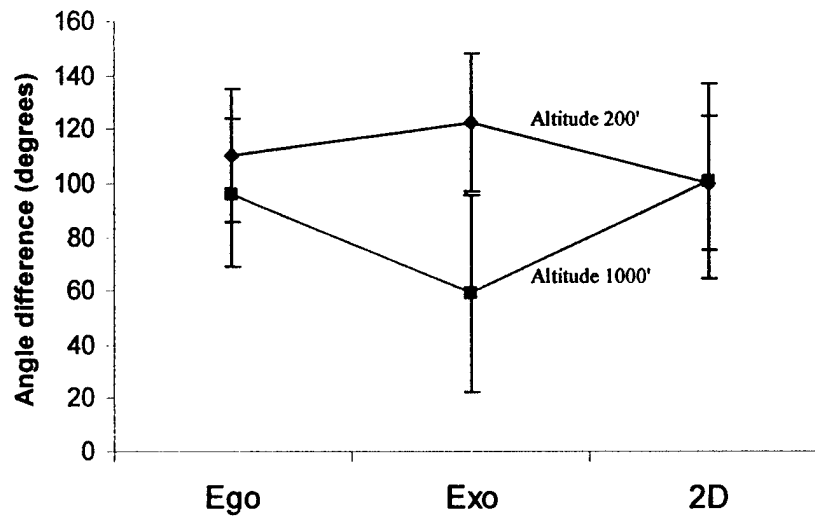
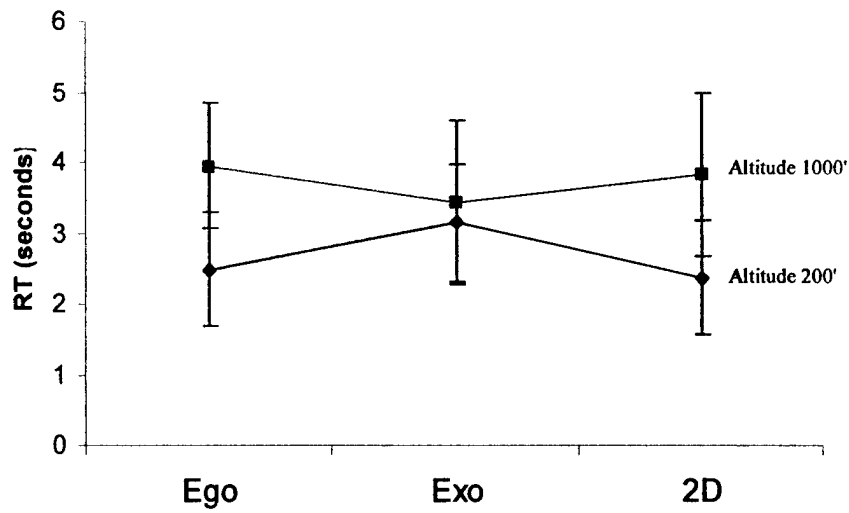
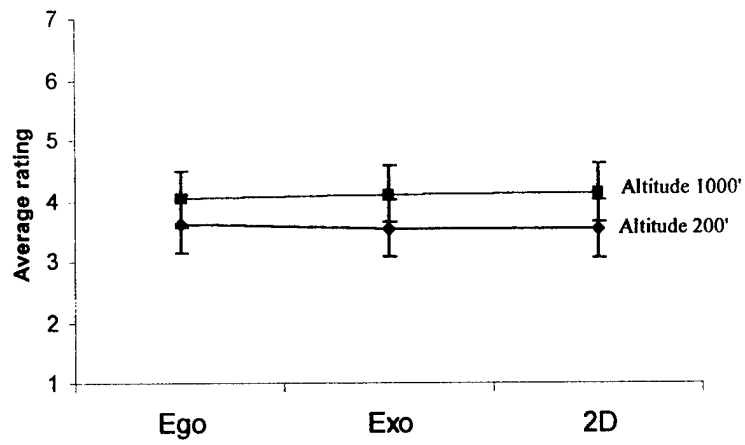


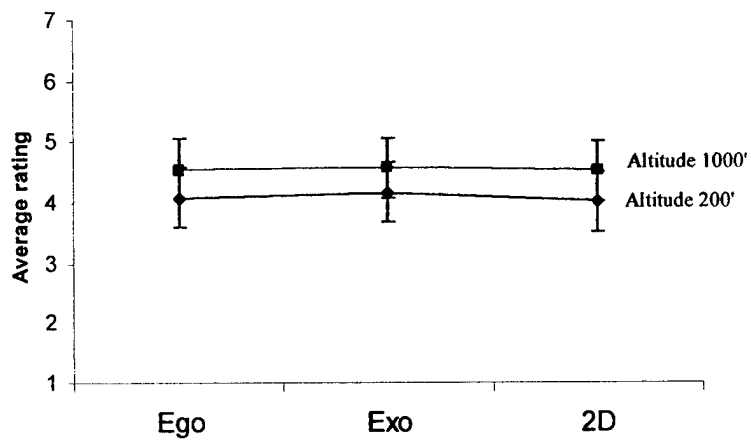
Figure 3.4b: RT for compensatory control input at hoverpoint.



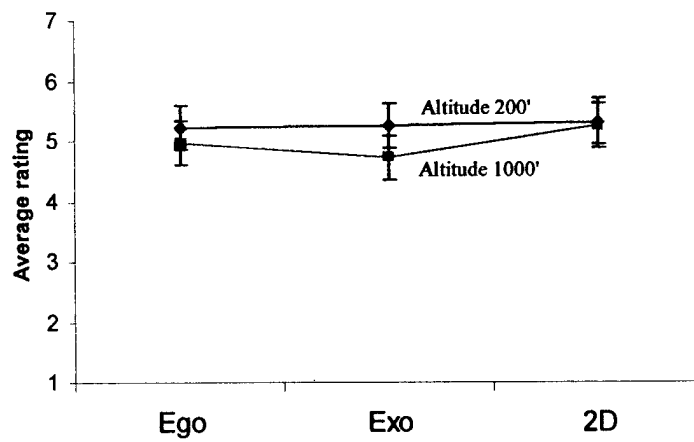
**Figure 3.5a: SART-Demand on attentional resources.**



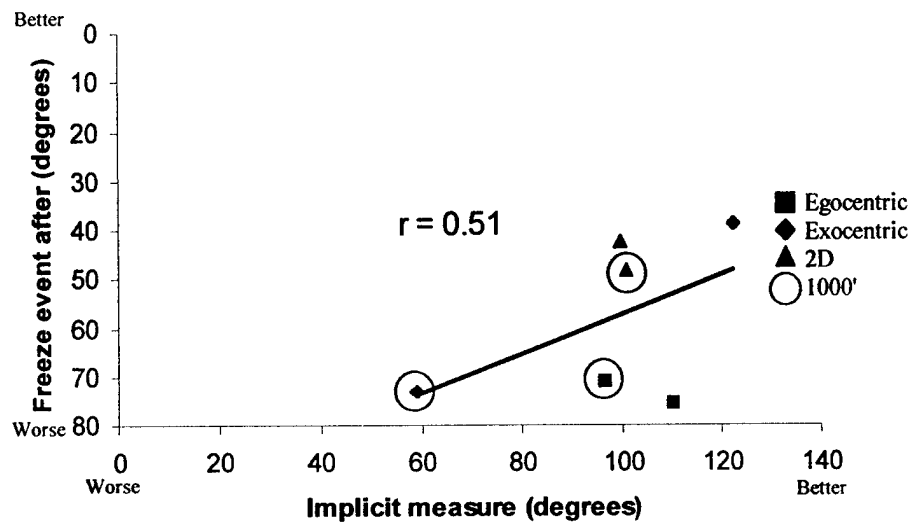
**Figure 3.5b: SART-Supply of attentional resources.**



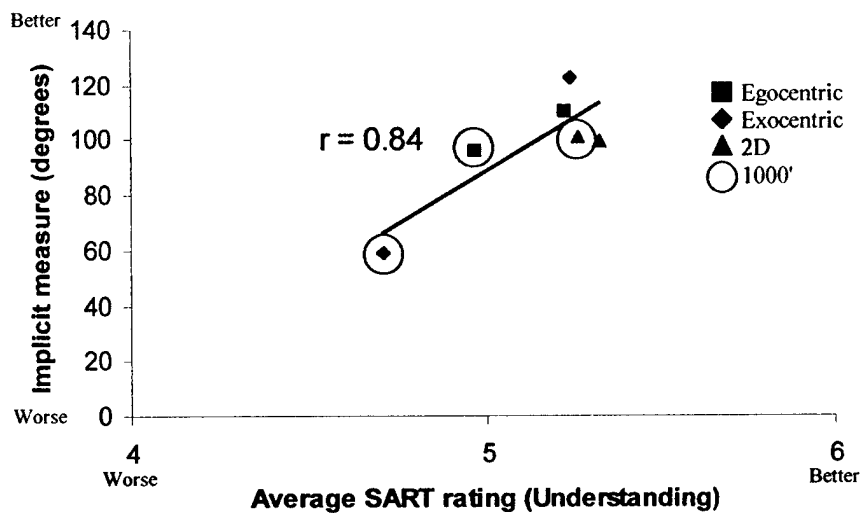
**Figure 3.5c: SART-Understanding.**



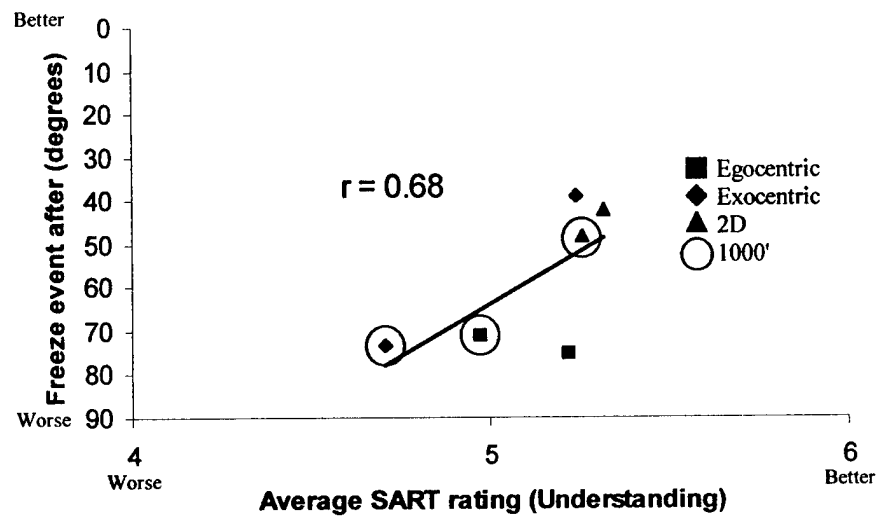
**Figure 3.6a:** Compensatory control input to freeze after event correlation.



**Figure 3.6b:** Compensatory control input to SART (understanding) correlation.



**Figure 3.6c:** Freeze after event to SART (understanding) correlation.



## DISCUSSION

This study sought to examine the effects that different frames of reference for electronic map displays have on pilot performance while flying multiple rotorcraft specific scenarios at two different altitudes. The primary variables of interest were the frame of reference for the map display (egocentric, exocentric, and 2D) and the altitude of flight (200 feet and 1000 feet) and their effects on pilot navigational ability and global situation awareness. Additionally, the degree to which the situation awareness measures agreed or disagreed with regards to the ability of the different displays to facilitate global situation awareness was investigated. In the following section, we explore the effects of the experimental manipulations on pilot navigational ability and global situation awareness, noting in our examination of the degree of agreement among the situation awareness measures.

### Navigational ability

The present study did not find an advantage for one type of map viewpoint over another in terms of vertical or lateral tracking performance (refer to Figure 3.1a and 3.1b), which does not support our first hypothesis that the egocentric display would provide superior local guidance ability. While this finding is inconsistent with previous evaluations of egocentric displays by Barfield et al. (1995), Wickens and Prevett (1995), and Olmos et al. (1998), it may be explained by the fact that this previous research on immersed displays was conducted during instrument flight rules scenarios in which no FFOV was presented to the subjects. These studies required subjects to navigate solely by use of the electronic map display, which meant they were "eyes-in" throughout the experiment.

In contrast, this study incorporated a FFOV that allowed the subjects to keep their "eyes-out" throughout the scenarios, simulating visual flight rules (VFR) flying. A similar frame of reference study by Olmos et al. (1997), also incorporating a FFOV, found results more consistent with those presented here, in that no difference in lateral or vertical tracking performance was found between display viewpoints. Olmos et al. (1997) only evaluated an exocentric and a 2D coplanar display, however, their results did suggest that the presence of the FFOV tended to mute the differences in navigation between display viewpoints. Our results suggest that VFR flying, in which a pilot spends a substantial amount of time with their "eyes-out", may diminish the effect of display viewpoint in supporting local guidance to the point that all three of the map viewpoints evaluated in this study (egocentric, exocentric, and 2D) provide equivalent navigation performance.

This equivalent performance, however, was not seen for two of the other flight performance measures; hazard contacts and stopping distance from hover points. The results revealed a significant display effect for the number of times the terrain was contacted during the scenarios (refer to Figure 3.2c), with the egocentric display having a significantly greater number of contacts than the exocentric or the 2D display. Also, further analysis of the egocentric viewpoint data revealed that most of the display effect was due to more terrain contacts at the higher altitude (1000 feet). This result may be attributed, in part, to the egocentric viewpoint's "keyhole" view of the world. In this study, the "keyhole" problem seems to have manifested itself only during the high altitude (1000 feet) missions when the terrain passed from the FFOV, but was still in front of the aircraft. Olmos et al. (1998) also used contacts with the surrounding terrain as a performance measure, and they too found that the egocentric display suffered with regards to terrain hazard awareness, because of problems associated with estimating the height of

approaching hazards. We infer that this "keyhole" cost for the egocentric display did not affect pilot performance at the lower altitude (200 feet) level because of heightened pilot vigilance concerning potential terrain conflicts associated with very low altitude flight, as seen by the higher rating for the understanding category of the SART across all three displays at the lower altitude (refer to Figure 3.5c). It is also important to note that Wickens and Prevett (1995) showed that attempting to alleviate the egocentric display's "keyhole" view by expanding the GFOV results in distortion, which might actually make obtaining accurate information more difficult. While we did not consider the number of terrain contacts as one of our global situation awareness measures, because it only represented hazards in the forward flight path, it nonetheless reveals to some degree that the egocentric display fails to support hazard awareness. These drawbacks have important implications for using an egocentric display in a rotorcraft cockpit to support a pilot's ability to closely skim over terrain and hazards.

The stopping distance from the hover point measure also revealed a significant display effect. When the subjects were required to transition into hover mode at the hover points, the "X" depicting the hover point was only visible on the map display, which required the subjects to obtain all information concerning the hover point location from the electronic map. Our results for this task were somewhat expected, with the 2D viewpoint providing more accurate performance than the egocentric and exocentric viewpoints (refer to Figure 3.1c). This finding is similar to those found by Merwin et al. (1997), Wickens et al. (1996), and Olmos et al. (1998) concerning the ambiguity costs associated with 3D displays when determining exact locations in three dimensional space.

However, an interesting interaction occurred, with performance at the higher altitude markedly worse than at the lower altitude only with the exocentric viewpoint. We infer that this

cost at high altitudes for the exocentric display may have resulted from perceptual biases in attending to the drop lines. These augmentations designed to improve the altitude coding on the exocentric display by displaying both the ground shadow and ownship connected by a drop line (refer to Figure 2.1b) have effectively improved pilots' tracking performance, but these augmentations have always been evaluated in the context of fixed winged aircraft flying high over the terrain (Olmos et al., 1997; Wickens et al. 1996). The higher the altitude of flight, the greater the separation, or distance, between the representation of ownship and the ground shadow. While these augmentations have helped resolve the problem of determining the pilot's location in space, at higher altitudes it may actually divide the pilot's attention along the length of the drop line. This means that when a pilot has to perform an exact positioning task, such as stopping on the "X" in this study, he or she may shift attention back and forth between the representation of ownship and the ground shadow, which may have an adverse effect on accuracy. In contrast, at very low altitude flight, such as the 200 foot level used in this study, the representation of ownship and the ground shadow are practically superimposed on one another, which eliminates the tendency for divided attention between the two. Further research is warranted to determine if this is indeed the case, which, if true, might mean that one of the costs usually associated with the exocentric display (difficulty in exact positioning tasks because of LOS ambiguity), may be lessened or eliminated for very low altitude flight.

Thus, the question of which electronic map display viewpoint is most suited for rotorcraft cockpits may depend not so much on support of local guidance ability, since the presence of the FFOV seems to mute the display differences previously observed in instrument flight rules flying, but rather, the ability of each viewpoint to provide sufficient and accurate information to support the unique tasks encountered during low altitude rotorcraft missions. Our results suggest

some potentially serious shortcomings for the egocentric display and its ability to provide adequate information for terrain avoidance. Also, both 3D displays supported worse performance overall for the exact position task at the hover points, but performance for the exocentric display may vary depending on the altitude of flight.

### Global situation awareness

For this discussion, we will focus on the three measures which we decided represented our most valid measures of global situation awareness; the freeze event after flag task, the implicit performance measure (compensatory control input), and the understanding category of the SART. The freeze event after the flag task ("freeze after" characterizing Endsley's (1987) SAGAT technique), was the only one of these three GSA measures that revealed a significant difference between the three display viewpoints (refer to Figure 3.3b), with the egocentric viewpoint resulting in significantly worse performance. This finding is consistent with those found by Barfield et al. (1995) and Wickens and Prevett (1995), and may again be attributed in part to the "keyhole" view of the world provided by the egocentric display, which results in the "out of sight, out of mind" problem whereby it is difficult to maintain awareness of hazards and obstacles within the 360 degree sphere around the aircraft. The flags were never visible to the pilots during the actual freeze event (since the IRIS map display was blanked), however, because the exocentric and 2D viewpoints provided a view of the aircraft within its surroundings, the flags were always visible in these two views immediately preceding the "freeze after" event. On the other hand, because the egocentric viewpoint only provides a small scale, forward looking perspective (3D) view of the world (i.e., "keyhole" view), the flag was never visible in the

egocentric display immediately preceding the "freeze after" event, making it difficult for the pilots to remember and locate the flag's position.

However, this measure did not reveal an advantage for the exocentric viewpoint over the 2D viewpoint in terms of GSA, an equivalence which does not support our second hypothesis that the exocentric 3D display would facilitate better global situation awareness than the 2D display. This inability to differentiate between the two display viewpoints regarding which provides the best global situation awareness is similar to results discussed by Rate and Wickens (1993), Olmos et al. (1998), and Wickens et al. (1996). One possible explanation for why no differences were revealed between the two display viewpoints may be that the flags were depicted on the map display and not in the FFOV. We based our hypothesis on the fact that the fairly congruent picture between the FFOV and the map display offered by the exocentric viewpoint at lower altitudes (Hickox and Wickens, 1997), would outweigh any of its associated costs. However, because the pilots did not have to locate the flags in the FFOV and then translate their location to the map, the benefits from the congruency between the FFOV and the exocentric map display might not have been realized.

Unlike the "freeze after" event, the implicit performance measure and the subjective estimation measure (SART) did not indicate differences between the displays. The implicit measure required that the pilots react to a crosswind at one of the hover points. There were a considerable number of times this task was missed at the higher altitude (refer to Table 3.1), especially for the exocentric and 2D display. This failure may be attributed to the amount of global optical flow perceived by the pilots at the different altitudes as the aircraft was perturbed by turbulence (Larish & Flach, 1990; Wickens, 1992), which was five times greater at the lower altitude level than for the higher altitude level. This means that movement caused by the

crosswind at the hover point was much more perceptible in the FFOV at the 200 foot level versus the 1000 foot level, which would also explain the quicker reaction times for compensatory input recorded for the low altitude scenarios versus the high altitude scenarios (refer to Figure 3.4b).

On the other hand, at the higher altitude hover points where motion from the crosswind was much less noticeable in the FFOV, the pilots had to rely more on the perception of motion provided by the map display. The distance a pixel moved per unit time across the screen during the crosswind event was measured for each display viewpoint, in order to determine the saliency of motion for each display. While the vertical movement per second was roughly equivalent between the egocentric, exocentric, and 2D viewpoints (approximately 0.06 cm/sec, 0.08 cm/sec, and 0.16 cm/sec respectively), the lateral movement for the egocentric viewpoint was dramatically greater than for the exocentric and 2D viewpoints (approximately 1.95 cm/sec, 0.127 cm/sec and 0.16 cm/sec respectively). This means that movement was much harder to detect during the crosswind event while using the exocentric and 2D displays, which would account for the increased number of misses for these two viewpoints at the higher altitude.

Although the implicit performance measure of compensatory control input did not indicate differences between the display viewpoints (refer to Figure 3.4a), these data did reveal a marginally significant interaction, with worse performance at the higher altitude than at the lower altitude only for the exocentric display. This interaction followed a similar pattern to the interaction revealed by the stopping distance from the hover point measure (Figure 3.1c). These two tasks were similar in that both the implicit performance task and the stopping at the hover point task required the pilots to stop at or remain at an exact position in space. We infer that the compensatory control input appropriateness cost for the exocentric display at the high altitude level may again be attributable to the pilots' attention being divided along the drop line between

the representation of ownship and the ground shadow, which may have adversely affected accuracy performance. This finding again suggests that further research is warranted in order to determine if this dividing of pilot attention along the drop line does indeed result in an associated cost in terms of accuracy for the exocentric viewpoint at higher altitudes.

For this study, we also wanted to evaluate the degree of association, or dissociation, between the different SA measures. A correlation analysis was performed between the implicit performance measure (compensatory control input), the "freeze after" event, and the understanding category of the SART (refer to Figure 3.6a-3.6c). Table 4.1 provides a summary correlation matrix. While only the correlation between the implicit performance measure and the SART understanding measure reached the standard 0.05 level of "significance", there appears to be a fairly good level of agreement between all of the measures in that all correlations are positive and at least 0.50. These results are somewhat inconsistent with those found by Endsley et al. (1998), in that those authors did not find any significant correlation between an objective measure of SA, the SAGAT, and a subjective measure of SA, the SART. The relatively high degree of agreement between the SA measures used in this study suggests that the measures are in fact measuring what we intended them to, which is the level of situation awareness achieved by the pilots during the scenarios.

	Implicit	Freeze after	SART(understanding)
Implicit	1.00		
Freeze after	0.51	1.00	
SART(understanding)	0.84	0.68	1.00

**Table 4.1:** Correlations between global situation awareness measures.

Despite the general agreement, however, the correlations were not perfect. For example, over half of the variance in the "freeze after" measure was not shared by the SART understanding measure. More specifically, the understanding category of the SART did not reveal a significant

difference between the display viewpoints and their ability to facilitate global situation awareness (refer to Figure 3.5c), possibly calling into question that measure's usefulness and appropriateness for display design evaluations. In particular, it failed to signal the loss of SA for the egocentric viewpoint in terrain contacts (refer to Figure 3.2c) and the difference in SA within the exocentric viewpoint in the implicit measure (compensatory control input) (refer to Figure 3.4a) and the stopping distance from the hover points measure (refer to Figure 3.1c). This finding of dissociation is inconsistent with the previous research by Selcon and Taylor (1990) concerning the ability of the SART to differentiate different cockpit designs, but it does support the concerns voiced by Endsley (1996) and Endsley et al. (1998) about possible shortcomings of the SART. This insensitivity of the understanding category of the SART to different display conditions is particularly troubling considering that the "freeze after" event, an objective measure, did reveal a significant difference between the ability of the display viewpoints to support global situation awareness. This failure by the SART to differentiate display conditions provides evidence that supports our third hypothesis that the SART may not be the best measure of the actual level of GSA achieved by the pilots.

Hence, the GSA measures revealed that the egocentric viewpoint suffers in its ability to facilitate sufficient global situation awareness. However, as with other studies (Rate & Wickens, 1993; Olmos et al., 1998; Wickens et al., 1996), there remains some uncertainty as to whether the exocentric viewpoint or the 2D viewpoint best supports pilot situation awareness.

## CONCLUSIONS AND FUTURE RESEARCH

In this study, we attempted to evaluate the effect different frames of reference for electronic map displays have on a pilot's local guidance ability and global situation awareness during low altitude rotorcraft specific missions. Our results suggest that the egocentric viewpoint should not be implemented into a rotorcraft cockpit, because it does not provide any better local guidance ability during VFR flying than the exocentric or 2D viewpoints, but it has higher costs in regards to its shortcomings for providing sufficient hazard and global situation awareness. The exocentric viewpoint and the 2D viewpoint both appear to offer equivalent local guidance ability during VFR flying, however, there is still uncertainty as to which of the two displays would provide better GSA performance. Considering the critical need for global situation awareness during low altitude rotorcraft missions, further research is warranted to try and determine which display best facilitates GSA. One possible area of interest is whether the exocentric or 2D viewpoint better supports the identification and location of hazards depicted only in the FFOV, which might reveal the benefits associated with the congruent picture offered by the exocentric view at low altitude levels. Also, the literature reveals several other variables of interest relevant to electronic map design for rotorcraft applications, such as scale or zooming, color, highlighting, and clutter, which need to be addressed. Given the pace of technological advancements in aviation, the study of these factors is both timely and appropriate.

## APPENDIX A

### PLEASE READ CAREFULLY!

#### Pilot's Instructions

Thank you for agreeing to participate in this research. It is important for the field of aviation that new designs of systems, such as electronic map displays, are thoroughly tested before becoming a permanent part of the hardware of any cockpit. It is through your participation that we can offer empirical evidence of the consequences of implementing such designs.

#### Mission Scenario

You are carrying a team of scientists conducting a geological survey for possible oil deposits. This survey requires very precise flights over the defined paths, in order to ensure that the scientists are able to accurately map critical terrain features. During these flights, there will be several points where you are instructed to hover, so that aerial photographs can be taken of the surrounding terrain. You will fly 6 missions, with three of them flown at an altitude of 200 feet ASL and a speed of 70 kts and three flown at 1000 feet ASL and 110 kts. Each mission lasts approximately 17 minutes, and consists of 7 legs.

The flying environment through which you will be flying contains a number of man-made hazards (powerlines and towers) and natural hazards (terrain and weather). It is of paramount importance to maintain the defined altitude and speed for each mission, to ensure accurate mapping measurements. This means that you need to avoid all hazards encountered during the flight, but also need to return to the defined altitude and path as soon as possible. Therefore, your primary responsibility is to fly each mission as accurately as possible, but avoid any hazards that jeopardize the aircraft. All terrain, weather, and powerline hazards are accurately depicted on the electronic map displays, however, none of the towers are depicted on the maps.

#### Electronic Maps

One of three different maps will be used for each of the 6 missions; 3D egocentric, 3D exocentric, or 2D planar. The 3D egocentric map display presents a view that corresponds to what you see from your seat looking out of the window. The 3D exocentric display presents a view from the perspective of being above and behind the aircraft. The 2D planar display presents a bird's eye view of the aircraft. See Figure 1-3 at the end of these instructions for a depiction of how these maps look.

#### Joystick Handling Characteristics

Throughout each mission, there will be two different modes of flight; forward flight and hover mode. For the experiment, you are considered in hover mode only when the airspeed equals zero. The "china hat" on the joystick controls airspeed, and therefore, it also controls the transition into and out of hover mode. The handling characteristics of the joystick change depending on your phase of flight.

During forward flight, the joystick controls the lateral and vertical axes of the helicopter in a manner consistent with standard aviation dynamics. Pushing forward/back on the stick causes a

decrease/increase in pitch, with the rate of change of altitude directly controlled by the amount of pitch. Moving the joystick to the right or left makes the helicopter roll right or left, respectively, with the roll angle directly proportional to the rate of change of heading.

During hover mode, pushing the joystick in any direction causes the helicopter to slew, or translate, in that direction, while maintaining the current aircraft heading. For example, pushing the joystick forward causes the helicopter to translate (move) forward, but does not result in a decrease in pitch. Likewise, moving the joystick to the right causes the helicopter to translate to the right, but does not result in a rightward roll or a change in heading. The "Twist grip" on the joystick is used during hover mode to change the heading, with a twist to the left causing the aircraft to turn to the left, or decrease heading, and a twist to the right causing the aircraft to turn to the right, or increase heading. Also, the top and bottom left side buttons allowed the helicopter to ascend or descend during hover mode. You will have an opportunity to practice with these dynamics before the start of the experimental trials.

### General Procedures

Each mission begins with the helicopter at the defined heading, altitude and speed for that particular mission. The box at the lower right corner of the map display will display the initial heading to fly, which you need to fly until you reach a waypoint or a hover point.

#### *Waypoints*

During forward flight, the need to turn to a new heading is indicated by the appearance of a "compass" on the left side of the screen (refer to Figure 1-3). A fixed red line on the compass depicts the new heading, and your current heading is indicated by a moving black line on the compass. As soon as the compass appears, you need to turn to the new heading, in order to align the black line (current heading) with the red line (new heading). When the two lines are aligned, the aircraft will be flying on the new heading. This new heading, which is redundantly displayed in the box at the lower right corner of the map, needs to be flown until the next waypoint or hover point. The compass will be visible for approximately 20 seconds.

#### *Hover points*

Throughout each mission, there will be four points where you need to hover. A black "X" indicating the location of the hover point will appear on the map display when you are within one-half mile of the hover point. You need to decelerate and transition into hover mode such that the helicopter is as close to the center of the "X" as possible, where the hover mode is again defined as happening when your airspeed equals zero. This transition is performed by using the "China hat" to decrease airspeed. Once your airspeed equals zero (i.e., you are in hover mode), the "X" disappears from the map display and the compass once again appears on the left side of the map. You need to use the twist grip on the joystick to rotate the helicopter (current heading depicted by the black line) to the new heading (depicted by the red line). When the two lines are aligned, the aircraft will be pointed in the direction of the new heading. The compass will remain on the screen for approximately 20 seconds. If a crosswind occurs at the hover point, you need to try and maintain the exact location where you entered hover mode, by moving the

joystick (do not increase airspeed). As soon as the compass disappears, you need to transition back into forward flight by increasing your airspeed back to the defined airspeed for the mission (70 kts for 200 foot missions, 110 kts for 1000 foot missions), which is accomplished by pressing upwards on the "China hat". The new heading, which is redundantly displayed in the box at the lower right corner of the map, needs to be flown until the next waypoint or hover point.

### *Direction indicating tasks*

Within each mission, there are randomly positioned pink flags visible only on the electronic map display. At unexpected times during each mission, all features on the map display will disappear, the scenario will freeze, and the helicopter will automatically be placed in hover mode. You will need to use the twist grip on the joystick to rotate the helicopter to point directly at the closest flag on the map. When you think you are pointing directly at the closest flag, click the uppermost left side button. As soon as the button is clicked, the map display features reappears and the mission resumes.

### *Verbal reports*

At predetermined times throughout each scenario, you will be asked to give a verbal rating of your current state of awareness. This rating will be based on three different aspects, which are:

- 1) Demand on attentional resources--this can be thought of as the instability of the situation, the variability of the situation, and the complexity of the situation,
- 2) Supply of attentional resources--this can be thought of as your arousal level, your concentration level, and how much your attention is divided between tasks, and
- 3) Understanding--this can be thought of as the quantity and quality of the information you are receiving and your familiarity with the situation.

The investigator will prompt you for your ratings by saying "SART", at which time you need to score each different aspect on a scale of 1 (Low) to 7 (High). A sheet of paper which displays the three aspects is attached to the map display monitor. You will verbally provide the number rating in the same order that the categories are listed on the sheet of paper. For example, I will say "SART" and you will say "3", "4", "2". This corresponds to a rating of 3 for demand on attentional resources, a rating of 4 for supply of attentional resources, and a rating of 2 for understanding. Try to provide the ratings quickly so that you are not distracted from your primary task of navigation and hazard avoidance.

### A Final Note

Flying the route as accurately as possible while avoiding all obstacles is your primary responsibility. A combination of keeping your eyes "out of the cockpit" and using the electronic maps will help you achieve these goals. At the completion of the full experiment (i.e., all subjects), we will award a bonus prize of \$20.00 to the pilot who performs the best in terms of maintaining flight parameters, completing the missions in a timely manner, AND avoiding hazards. Two additional bonus prizes of \$10.00 will be awarded to the second and third best performers. Thank-you again for your participation.

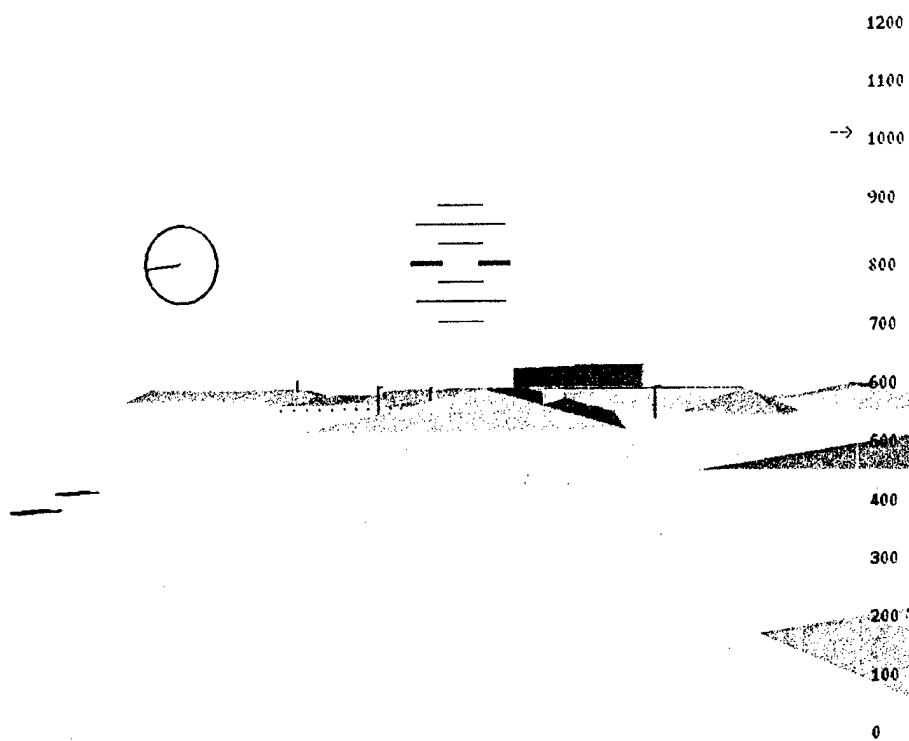


Figure 1. Egocentric viewpoint.

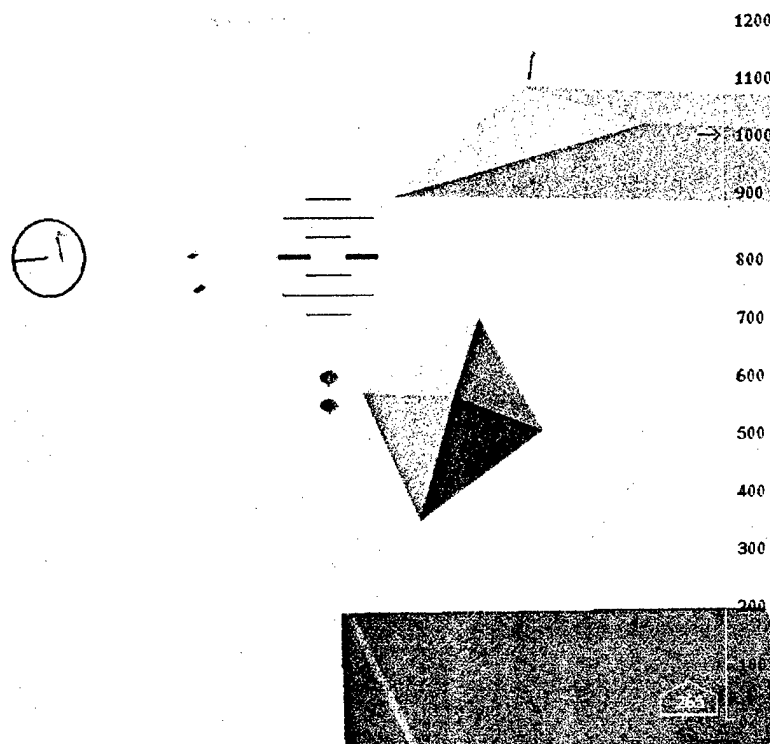


Figure 2. Exocentric viewpoint.

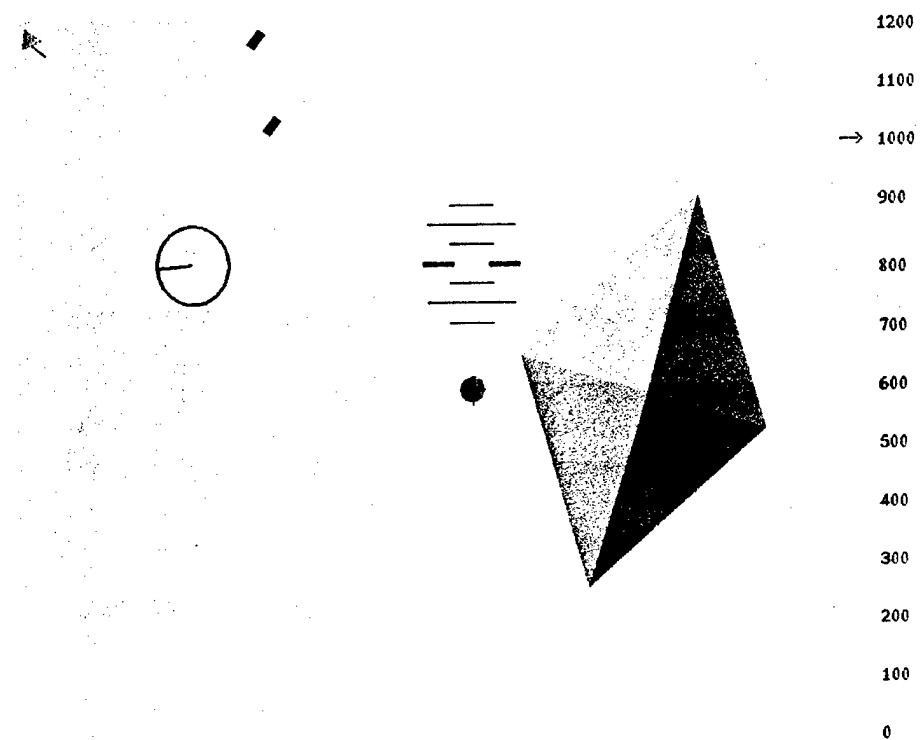


Figure 3. 2D planar viewpoint.

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